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TREATISE ON

RIVERS AND TORRENTS,

AND ON RIVERS THAT CARRY SAND AND MUD.

AND AN ESSAY ON

NAVIGABLE CANALS.

TRANSLATED FROM PAUL FRISI.

With Illustrations.

LONDON :—JOHN WEALE.

A

TREATISE

ON

RIVERS AND TORRENTS;

WITH THE

METHOD OF REGULATING THEIR COURSE AND CHANNELS.

BY

PAUL FRISI,

A BARNABITE, PROFESSOR AT MILAN, F.R.S. OF LONDON, MEMBER OF THE INSTITUTE OF BOLOGNA—OF THE IMPERIAL ACADEMY AT PETERSBURG—OF THE ROYAL ACADEMIES OF BERLIN AND OF STOCKHOLM, &c., AND OF THE ROYAL ACADEMY OF SCIENCES AT PARIS.

TO WHICH IS ADDED,

AN ESSAY ON NAVIGABLE CANALS.

TRANSLATED BY

MAJOR-GENERAL JOHN GARSTIN,

OF THE BENGAL ENGINEERS.

A NEW EDITION, CORRECTED.

LONDON:
JOHN WEALE, 59 HIGH HOLBORN.

1861.

ADVERTISEMENT OF THE NEW EDITION.

THE Work of Paul Frisi, as well as other practical Italian writers, on Rivers, Water-ways, Irrigation, Canals, &c., having, both theoretically and practically, elucidated the several subjects (more especially Frisi) connected with the navigable improvements of countries essential for their civilisation and commerce, not only in Europe but in India and America, have induced professional men and others to study recently the literature of this branch of Engineering, and which induced the late Major-General Garstin to make a translation from the original work in the Italian language. The General states:—

"The first edition of the work, as stated by the author in his preface, was printed at Lucca, in 1762: the second, with additions, at Florence, in 1770, eighteen years after the appearance of the first. The author, however, was a native of Milan, where he was born in 1727. During his education, his studies were directed by the Regular Clerks of St Paul, or Barnabites, as they were more frequently called, from the Church of St Barnabas, at Milan, which had been

bestowed on their order. He took the habit of the order at the age of sixteen; became Professor of Mathematics in the University of Milan; travelled afterwards through France, England, and Holland; and visited the principal cities of the rest of Europe. He was eminently skilled in Hydrometry and Hydraulics; so high, indeed, stood his reputation, that all the works dependent on a knowledge of Hydrostatics, executed in Italy in his time, were submitted to his inspection and judgment. Maria Theresa, Catherine II., and Joseph II., honoured him with their patronage; and the most celebrated academies and societies of scientific and literary men enrolled him among their members."

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December 1860. J. W.

PREFACE BY THE AUTHOR.

In Italy, the first seeds of Geometry, of Algebra, of Mechanics, of Optics, and of Astronomy, were sown; and in process of time these sciences extended themselves beyond its mountains and the sea. Galileo, Cardan, Cavalieri, Viviani, Cassini, Borelli, Grimaldi, Manfredi, and Grandi, were the men of genius who gave rise to that happy revolution which has taken place in these sciences during the two last centuries. But it is not to Tuscany and Lombardy alone that mankind are indebted for the great discoveries which have been made respecting the methods of Calculation, the Laws of Motion, and the System of the Heavenly Bodies. A great part of these are due to France, to Germany, to Holland, and above all to England; where the trancendent genius of Newton has passed far beyond those limits which had bounded the researches of all who had lived before him.

Hydraulic Architecture arose, advanced, and almost attained perfection, in Italy, where they have written on every point connected with the theory of torrents and rivers, the conducting and distribution of clear

and turbid waters, the slopes, the directions, and the variations of channels; and, in a word, on the whole range of Hydrometry and Hydraulics. We owe all that has been done on these subjects to Castelli, Viviani, Zendrini, Eustace Manfredi, and especially to Dominico Guglielmini; who has left us his great work on the Nature of Rivers. Mariotte, Picard, Genneté, and some other celebrated Ultramontanes, have added but little to what had been done by our Authors, to whom M. d'Alembert, in the Dictionnaire Encyclopédique, ascribes the chief improvements which have been made in these sciences. Nor have the speculations of the Italians been confined in their effects to the bare honour of writing books. They have, moreover, contributed much to the salubrity of the air, to the ease of inland navigation, and to the fertility and security of the plains.

The Po, which, formerly divided into several branches between Placentia and Parma, had converted a considerable part of Lombardy into a marsh, has been circumscribed by dikes, and confined within a single channel of a suitable depth; whereas the Great Rhine, divided and subdivided as it is in Holland, has considerably elevated the bottom of its bed; and, whilst it renders the situation of the adjoining lands daily worse and worse, is threatening them incessantly with utter destruction. The celebrated Muratori, in his twenty-first Dissertation on the Antiquities of the Middle Age, treating of the physical geography of Lombardy in the ninth and tenth

centuries, has clearly shown how much agriculture had gained since that time between the Tesino and the Adriatic. Since that time, also, meliorations have taken place over a great part of the Vale of the Arno in Tuscany, the Vale of the Chiana, and the Plains of Leghorn and of Pisa. The mechanism of irrigation has been carried to the highest perfection in the Canal of Muzza, which is supplied from the Adda, and distributed and divided all over the Lodesan. Other navigable canals, derived, with excavations of immense labour, from the Adda, the Tesino, the Reno, and many other rivers, have proved of the greatest utility to the commerce of our Provinces. The invention of the method of retaining water by means of sluices and locks, made in the fifteenth century, and reduced to practice in the Paduan, led the way to the junction of the two navigable canals of the Adda and of the Tesino, which Leonardo da Vinci formed at Milan; and this junction has since served as an example and model to several other navigable canals, particularly to that of Languedoc.

The Reno and the Po are the two rivers that have chiefly engaged the attention of the Italian Mathematicians. Formerly the Great Po reached Ferrara, receiving in its course the Panaro and the Reno; and some miles below, at the point of the Polesine of Saint-George, it divided itself into two branches, called those of Primaro and of Volano. In the twelfth century, a part of the Po turned off to the left, a little above the confluence of the Panaro, and formed another

branch, which was afterwards named the Venetian or Lombardy branch. The Venetian Po gained gradually on the Ferrara branch, and in the last century entirely absorbed it. This event, so fatal to the commerce and navigation of that illustrious city, occurred some years after the Reno had ceased to flow into the Great Po. It was in 1604 that the Reno, obstructed by the alluvions of the Ferrara branch, and retarded by the diminution of its waters, which were lessening daily, spread itself over the valleys of the Sammartina. These valleys were soon fertilized by the abundant deposits of the Reno, and so considerably raised, that its stream, unable any longer to pass in that direction, overflowed its embankments, and inundated the finest and most fertile plains of the Bolognese. The five other lower torrents, the Savena, the Idice, the Centonara, the Quaderna, and the Sillaro, finished their courses also on these plains. All these waters, running without embankments and without beds, formed deep bottoms, from which they issued but slowly, and only in part, in approaching the sea by the ancient and tortuous bed of the Primaro. This sad spectacle interested deeply the most eminent mathematicians of Italy, and gave occasion, if not to an effectual remedy for such serious evils, to at least that degree of perfection to which the theory of running waters has been carried.

Castelli, Cassini, Viviani, Guglielmini, Grandi, Manfredi, and several others, proposed to remove the cause of these disasters, by causing the Reno to re-enter the Great Po. They were able to solve, in a masterly

manner, all the physical and hydrometrical objections that were urged against the project; but political obstacles caused it at last to be abandoned. This scheme once laid aside, all the other proposals were reduced in effect to two: the one, to form a bed for the waters, amidst the soil which they had themselves deposited in the lower part of the lands actually overflowed, and to make the lower trunk of the Primaro serve for their discharge: the other, to turn the course of the Reno above the low grounds, and the breaches which caused these inundations, by forming for that river a new bed, which, commencing some miles below Bologna, should receive in its progress all the lower torrents, and convey them, united and enclosed between its embankments, to the sea. Guglielmini gave weight to the former project: Eustace Manfredi successfully combated the latter. Gallioni and Gabriel Manfredi formed the plan of a cut, in length eight miles, to give the waters of the Reno a ready outlet into the Primaro, and to receive at the same time the waters of the Savena and those of the Idice. This was the celebrated Benedictine Canal, which would most assuredly have changed the face of the Bolognese, if so many accidents had not attended its execution. The principal of these accidents was, that as the Idice, before it fell into the cut, from a height of about eighteen feet, had been but feebly sustained by a weak sluice placed at its entrance, this sluice was forced; and the torrent considerably lowered and enlarged its bed, carrying so great a quantity of earth

and sand from its bottom and torn sides into the cut, as in a great measure to fill it up. Another accident also occurred; the banks, which were laid on quaggy foundations in a valley through which it was necessary that the canal should pass, gave way. The first accident had a great influence on the second; for the deposits left by the Idice, obstructing the free course of the waters from the Reno into the Primaro, rendered the consequences of the ruptures which took place higher up still more serious.

I had determined to visit Rome in 1760, at the period when the mathematicians of Bologna and of Ferrara were deeply engaged in the controversy concerning these waters. The former proposed to repair the Benedictine Canal; and to convey by it all the streams into the Primaro, raising a new embankment on its right side, and repairing and heightening the old dike on the left. The other party reproposed, with some alterations, the old project of making a new bed for the Reno and the other torrents; and urged, as a principal objection to the first scheme, that the Primaro, for the space of ten miles, from the Benedictine Canal as far as Bastia, was very irregular and winding, and of little declivity; and, consequently, that the assemblage into it of all the waters of the Bolognese would greatly endanger the lower Polesine of Saint-George, which borders on it. This was to me an imperious call to enter into this grand dispute. I was of opinion, that the point was not merely the formation of a new bed for the reception of all the waters;

and, that the interests of the Ferrarese might be sufficiently consulted by continuing the Benedictine Canal straight on to Bastia, an extent of seven miles, across the narrowest section of the valley of Marmorta, where the soil is firmest and of the best consistency. The other modifications, that appeared to me calculated to induce both parties to adopt the plan of the Primaro, were reducible to the five following heads: 1st, To form a bed for the Reno, amidst its own alluvions, from the breaches in its dikes to the commencement of the Benedictine Canal. 2d, To remove the earth deposited by the Idice, to close the breaches in the Canal, and to complete it. 3d, To introduce the Savena into the Canal, and to secure the present entrance of the Idice. 4th, To convey, by an aqueduct, under the bed of the Idice, all the drainings of the country between the Idice and the Savena. 5th, To join the Centonara to the Quaderna, and afterwards to unite the Quaderna with the Sillaro, as far as Bastia. This plan was then approved, and unanimously subscribed, by the mathematicians both of Bologna and of Ferrara.

In this manner, I laid before them the mere outlines of the plan, reserving to myself, on a careful examination of the localities, to determine all the details in the order and execution of the works. After having personally surveyed the whole, and scrupulously examined all the levels taken by the men of science employed by the parties interested throughout the plain of the Bolognese, I stated my sentiments

more at large, in a book printed at Lucca in 1762, *On the Method of regulating Rivers and Torrents, particularly those of the Bolognese and of Romagna.* Since that period, the dispute has become so violent and noisy, and the writings for and against all the schemes have so multiplied, that I have felt little inclination to quit more peaceful studies, and especially that of Algebra, to add to it.

At Rome, the Congregatio ab Aquis were occupied in the consideration of four different projects: two of these were to form a new bed, which, commencing at the Samoggia, a little below the confluence of the Lavino, should afterwards receive the Reno, and the other torrents and drainings, and carry them in one stream, through tracts more or less elevated, into the Primaro, at Saint-Albert, about six miles above its opening into the sea. The two remaining schemes were, to continue the Benedictine Cut, according to the one through the upper part of the valley of Marmorta, as far as Saint-Albert; according to the other, through the lower part of the same valley, as far as the opening of the Santerno into the Primaro. These four lines having been rejected, three mathematicians were directed to visit the sites, and propose some medium. They were of opinion, that no injury was to be apprehended to the lands of Ferrara from conveying directly into the Primaro all the waters of the Benedictine Canal; and, moreover, they concurred entirely in the ideas first suggested, of repairing that cut, of throwing into it the stream of the Savena, of

carrying the aqueduct under the present bed of the Idice, and of uniting the Quaderna and the Sillaro with the Reno.

Matters being in this situation, I consented to this Second Edition of my Treatise, which I have augmented with several observations, made in my journeys on both sides of the Apennines, the Alps, and the sea.

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A TREATISE

ON

RIVERS AND TORRENTS.

BOOK I.

OF RIVERS AND TORRENTS THAT FLOW OVER GRAVEL.

CHAPTER I.

ON THE ORIGIN OF RIVERS, AND THE CAUSES AND PHENOMENA OF THEIR FLOODS.

A RECLUSE philosopher may, in the silence of his study, start doubts and seriously inquire, whether rivers derive their origin from the sea, rather than from rains and melted snows. A philosopher, who travels, can have no doubt on the subject, when he has once seen the bed of any river, and has taken the pains to trace it to its first source.

When employed to mark out the high road now making from Modena to Pistoia, through the province of Frignano, I was compelled to follow the stream of the Panaro as far as to the mountain of Boscolongo; and then, descending on the opposite side, I proceeded

along the banks of the torrent Lima for several miles. At another time, I ascended, for my own satisfaction, the river Magra from its entrance into the sea, near Sarzana, to seven miles above Pontremoli; and I visited the seven sources, which, at the point of their union, assume the name of Magra. Then, passing over the summit of the mountain, I observed, within the distance of half a mile, the twelve sources of the Tàro, which I followed for several miles. On various occasions, I have traced for a great way the courses of other rivers,* and I have never perceived the slightest reason to suspect that they derived their origin from any but meteorological causes,—rains, and snows.

In ascending the bed of a river, it will be observed to be spread over with substances that are constantly increasing in size; and it will be remarked, that, in equal spaces, the fall of the waters becomes greater, and their quantity less. This diminution proceeds in a continued succession of very small differences, and with so imperceptible a gradation, that, to be justly estimated, it must be seen. The principal trunk of the river is formed of several branches smaller than itself, and these, of a great number of ramifications constantly and gradually decreasing in size. All the bottom and the banks of the receiving and entering streams are covered with innumerable minute veins, which continually supply small threads of water. The first springs are very trifling, as are all the first rills, which, flowing from so many different points, successively form or swell the stream. They may be

* The Po, for example, the Tesino, the Adda, the Reno, the Savena, the Idice, and the Fersina, as well as others, with about twenty small torrents.

observed distilling and trickling, drop by drop, down the damp sides of the hills and the mountains; and the ground in their vicinity is so drenched and even saturated with water, that wherever a small excavation is dug, it is instantly filled. In a word, it is evidently seen, that all the running waters issue by little and little, at all points of the surface, from the very crust or shell of the earth; and that it is a physical reverie to imagine that there are subterranean ducts, which convey a whole river from the surface of the sea to the summits of the mountains.

To demonstrate this more fully, it is to be observed, that the ordinary quantity of the waters that flow in rivers is very small in comparison with that which is discharged in moderate and great floods. Rivers, in high floods, increase to many times their usual height. The Seine, at the Pont-Royal of Paris, has sometimes in summer only three feet, or three feet and a half, of water; but in the great floods of 1714, 1719, and 1760, it rose to twenty feet and a half.* The Po, in ordinary floods, quadruples its height; so that, supposing the breadth of its bed to remain the same, the Po, in one day when flooded, yields as much water as in eight days when it is low. If to this be added the great enlargement of the bed in the time of the floods, and it be also recollected, that the Po is generally flooded two or three times a year, each flood lasting from thirty to forty days, besides several other moderate swells, there will be no difficulty in allowing that the greatest quantity of water flows during its floods. There can be no doubt, however, that these floods are caused solely by rains, or by snows. A river, indeed,

* In 1740, it rose to 25 feet; in 1751, to 21 feet; and in 1763, to 22½ feet.

is never perceived to increase without plentiful rains, or without its being known that a great melting of the snow has taken place in the mountains. The peasants have sure indications of the approaching floods in the state of the air, the prevailing winds, or other meteors; and they know when to remove, in sufficient time, whatever may be requisite, out of the way of the torrents, which are subject to sudden rises.

We have another proof of this truth in Italy, where the greater part of the mountains and hills are composed of light soil. The Thames and the other rivers in England do not bring down many sorts of substances with their streams; and they preserve their transparency in a sufficient degree even during their floods.* It is from this cause that the arches of the Old, or London, Bridge, and those of the New, or Westminster, Bridge, are equally free, and that the bottom of the whole of the river is not sensibly raised.† With us, the waters, which fall on the tops of the mountains, detach and bring down a great quantity of various substances. The coarsest sands, gravels, and stones, are swept on, in irregular masses, by the impetuosity of the waters; and are precipitated here and there, without any fixed direction, to the bottom of the stream, and abandoned in succession, at different distances from its source. The largest stones, and those of which the forms are the least regular, remain always in the upper trunks of the rivers; and,

* This, at the present period, must be considered an error; nevertheless, when the Metropolitan Board of Works have carried out their new scheme, this statement may yet be proved correct.

† London Bridge is greatly obstructed; and it is owing to the quantity of ballast taken out that the bed of the river is not raised.—Fr. Old London and Westminster Bridges do not now exist. The new ones have much less obstruction to the tidal currents.—Edit.

as the fall and force diminish in the lower, the streams there carry forward only the round stones, and gravels and flints always lessening gradually in size. The coarse sand extends far beyond the limits of the gravels. The fine sands, and the earthy particles, with others of a similar nature, being in specific gravity but a very little heavier than water, are raised from the bottom by the violence of the motion, and, from the difficulty which they encounter in sinking, form one body with the waters, which they deprive of their transparency, and reduce to that state in which they are properly called turbid. The change of colour that is remarked on the first rise of the streams is a certain indication of their course, and of the places from which they come.

Another important observation offers itself. All great rivers, and their subsidiary streams, commencing at different distances, their freshes do not come down in the same periods of time; and, supposing that there is a general rain in the mountains, or a sudden melting of the snows, those torrents, which have the least distance to flow before they reach a certain point, are the first that are there flooded. Thus it frequently happens, that an affluent is turbid, when the recipient is clear; and that, on the other hand, the fresh of the affluent having passed by, the recipient stream alone remains discoloured. It is then that one may clearly perceive that the waters of the subsidiary continue to flow, for a considerable distance, along their own margin, without mixing in the smallest degree with the waters of the principal stream.* This has been

* It has frequently been observed at the confluences of the Gogra, the Soane, the Gunduck, and the Coosa, where they join the Ganges.

already observed by Father Grandi, and by several others, in the Tesino, and the Panaro, affluents of the Po, at the time of the visits which were made in those parts by public authority; and I have myself made similar observations at the mouths of the Tesino, and of the Lambro. I there observed also, that as the soils on which the waters that occasion the floods in these rivers fall are of a different nature, so the turbids which they bring down are likewise of different qualities.

To these variations, which arise from the difference of places, must be added those occasioned by the difference of times. The changes which have taken place in these latter ages on the surfaces of the mountains, the clearing away of the woods and brushwood, and the cultivations very unadvisedly undertaken on the steepest declivities, are the unfortunate causes why the rains carry into the beds of streams a much greater quantity of various substances than they formerly carried: because the obstructions that were presented by bushes and plants having been removed, the waters flow more abundantly, and with greater celerity, into the rivers; and passing over lands stirred up by the plough and the spade, they are more loaded with sands, earths, and stones, than formerly.

In short, all the phenomena of floods; the laws by which they increase and diminish; the substances which they sweep along with them; all clearly point out, that they derive their origin from the rains that fall on the declivities of the mountains and into the beds of the rivers. Seeing, then, the greatest quantity of water, as has been before observed, is brought down by the rivers in the time of their high and moderate

floods, it would be unreasonable not to admit that the waters, when low, have the same origin.

On the other hand, it is certain, that in whatever manner the waters of the sea, shaken, filtered, and, if it is possible, rendered fresh in the bowels of the earth, could reach us, they would be always different from other waters, which fall directly from the clouds. But the water of a river, whether at its greatest or lowest height, is always of the same quality. At Paris, and at London, where the water of the Seine, and of the Thames, is used all the year round, when it has passed through the same filters, and is purified of all its earthy particles, no difference is perceptible, either in taste or colour, at various times, or in different seasons of the year. Chemistry itself has not been able to point out any sensible difference. It is therefore conclusive, that the waters in rivers, whether they are high, or are low, whether in time of rain, or in dry seasons, derive their origin from the same causes.

Moreover, the droughts that are felt in the plains, particularly in the summer season, never take place on the summits of the mountains. The absolute quantity of rain that falls every year is greater in proportion to the proximity of the places to the slopes of the most elevated mountains. At Paris, it is about eighteen or twenty inches. At Milan, it is about forty inches; and in 1765, it exceeded forty-seven. In the mountains of Garfagnana, it extends from ninety to one hundred inches. Tempests and rains are always more frequent and more plentiful in mountainous districts. The summits of the Alps and the Apennines are covered, even in summer, with snow. The fogs, which envelop the mountains, keep

up a perpetual humidity, and supply the place of a continual and invisible rain. There is, therefore, on the mountains a sufficient quantity of water to afford a constant supply to the sources of rivers, even when the lowlands experience the greatest droughts.

Thus, it is useless to enter at length into all the calculations of Mariotte, Halley, and several others, who, starting various hypotheses very vaguely, on the velocity and capacity of the principal rivers, have sought to prove, that the quantity of water, which falls annually from the heavens, be it in rains, or in snows, is much greater than all that is carried off by the rivers; for it is a fact, ascertained purely by observation, that all the water of torrents and rivers, in great and moderate rises, is carried into their beds from melted snows, or from general rains which fall chiefly in the spring and autumnal seasons; and it is likewise simply a fact, that the rains, the fogs, and the perpetual snows on the mountains, supply the remainder in the greatest droughts of summer.

The great reservoirs and hollows, which are found on the summits of mountains, are filled by the heavy rains; and, as the quantity of evaporation is less, lakes are found there throughout the year. There are some on the mountains of Pistoia, near the sources of the Ombrone, and of the Reno; and I have seen many others in divers places. Scheutzer and Vallisnieri imagined that these lakes and other reservoirs of water resembled so many siphons, excavated internally in the chalk, sandstone, and other substances that compose the bony parts of mountains, and serving to supply the first springs of rivers, which take their rise sometimes from the tops of other less elevated mountains. For my own part, I am not aware, that

any springs rise on the summits of mountains, having always discovered them dispersed here and there on their slopes. I have, besides, observed, that in the vicinity of springs all the grounds were damp and moist, as if saturated with water; and it is certain that the cracks and small channels in the uncultivated ground on the tops of mountains, permit the rains to enter and insinuate themselves much more deeply than they can do in the cultivated lands of the plains, where nothing but the mere surface is penetrated by the moisture.

It is therefore needless to devise any system. The quantity of rain, and of snows that fall and melt, the quality of the lands, which imbibe them on the tops of the mountains, and the inclination of the slopes, which permit them to run off freely in the plains below, are sufficient to explain the phenomena which are observed in the origin, the course, and the swell of all rivers.

CHAPTER II.

ON THE SUBSTANCES BROUGHT DOWN BY RIVERS.

We remarked, in the preceding chapter, the regular gradation in which, when descending the bed of any river, we meet with, first, large and rough masses of stones; afterwards, round stones, smaller in succession; then, large and small gravel; and, last of all, sand and pure earth. This gradation is a fact everywhere constantly observed: it remains that we assign for it an adequate cause.

Guglielmini, in the sixth chapter of his work treating on the nature of rivers, is of opinion that the sands are nothing but stones pulverised, just as stones are often composed of sands bound together. He has besides observed, that stones, impelled by the impetuosity of the water, rolling over and striking each other, must break and continually wear away. He considered the polish which gravels take in streams as a manifest sign of their abrasion; and that the incessant murmur that is heard in the beds of rivers, which carry gravels, was less the effect of the mutual shock of the waters, than of the continual striking of the stones against each other. In a word, he asserts that stones, by their mutual collision and friction, become round, constantly diminish in bulk, become by degrees either large or small gravel, and are at last ground down and reduced to common sands.

As for myself, I am of opinion that round stones, gravels, and sands, are substances originally prepared by nature, and spread all over the globe: that stones, turning and rolling on the bed of a river, may there receive a greater degree of polish, and sands may possibly become smaller; but that stones and gravels, striking and rubbing against each other, however great may be the force, can never be converted into sand; and, finally, that the constant diminution in the size of these substances in rivers arises from the lessening of the fall, and the decrease of impetuosity in the running waters, which, leaving the largest and roughest stones in the upper parts of the beds, convey to considerable distances only the round stones and gravels constantly and gradually smaller and smaller.

In the first place, whatever may be the force and effect of friction in the beds of rivers, it must necessarily be granted that the sands which are scattered about, or heaped together, in such quantities on the mountains, on the plains, and even under the surface of the earth, are original sands, and as ancient as the Creation. In fact, what could have been the material causes which could, by any accident, have concurred to form those immense, deep, and uniform layers of sand in Numidia, in the vast deserts of Tartary, and in so many other plains at a distance from all rivers, and from the sea? Even in plains that are watered by rivers and torrents, and where there are found very large beds of sand, there is no correspondence between the distribution of these layers of sand and the course of the rivers and torrents.

In the Memoirs of the Royal Academy of Sciences at Paris, for the year 1746, M. Guettard, in his Mineralogical Chart of France and England, remarking

on the distribution and bearings of the three layers of gravel, of sand, and of clay, expresses his conviction that the substances which are there discovered enter into the original composition of our globe. The subterraneous beds of sand and gravel discovered in Lombardy and in Holland, as well as in many other places, are so abundant, and of so great a depth, that it is quite impossible to imagine they could be formed from substances ground down and deposited by the action of rivers. There is also discovered in hills, and in mountains, where, to all appearance, there has never been any river, an immense quantity of sands, and of large and small gravel. M. Targioni, in his "Travels through Tuscany," has given an ample description of the various beds of all these substances that are there met with in several hills. At Saint Loup, at Saint Cassien, and at other places, where the road is cut through the mountain, all travellers may observe how the beds of sands, of gravels, and of stones, round and smooth, are disposed. The Plain of Lombardy, which is comprehended between the two upper trunks of the Adda and the Tesino, as well as all the plains at the foot of the mountains, are amply spread over with sands, and large and small gravels.

If, therefore, the sands of mountains, of hills, and of so many extensive plains, are original substances, there is no reason to believe that those which are found in the beds of rivers and torrents, and which perfectly resemble the former in figure, hardness, and weight, have a different origin, and that they have been formed from the grinding down of stones and gravels. It is also improbable, that round smooth stones striking and rubbing against each other, could

detach so many small irregular stones, furnished with such numerous sharp-pointed angles, as sands are. Besides, if the essential and intrinsic difference between sand and stones is observed, it will clearly appear, that, generally speaking, sands do not compose stones, and that stones cannot be resolved into sands. In our rivers, as in the Arno, the Reno, the Adda, the Tesino, &c., it is rather uncommon to find such stones as are properly termed sandstones, from their being composed of sands united together; even fusible and vitrifiable stones are but seldom found. The stones and gravels of our rivers are for the greater part calcareous; and I should think that I assigned a very favourable proportion in asserting, that scarcely one in a thousand of the stones of the Reno will be found to be vitrifiable, while all the rest will be calcinable. Nevertheless, the sands of these rivers, at least when they are cleansed from the muddy particles, are for the greater part of a siliceous substance, angular, very hard, and vitrifiable. The particles of a calcareous nature found mixed with them are very few, and out of a thousand grains of sand scarcely five can be calcined. The rest are fusible and vitrifiable. Whence it follows, that the stones and gravels in our rivers, at least the greater part of them, are not composed of united sands. And as the shock and friction of these substances cannot change the nature of the minute particles of which they are composed, it is therefore impossible to believe that sands are small pieces of stone divided and pulverised, as Guglielmini imagined.

I will add to these observations some experiments. I passed over a grindstone, for a considerable length of time, various sorts of river stones, and I put a large

quantity of them into wooden boxes, which were violently shaken for many hours; all that was taken off by the grindstones in the first experiment, and that was found in the angles of the boxes in the second, was merely a very fine whitish dust, which a breath dispersed in the air, and which, when thrown into standing water, could never entirely subside; and although, on opening the boxes, broken pieces were sometimes found, and sometimes scales from their sections, it never happened, however long they might have been shaken, that I had it in my power to obtain a single grain of sand, either from grit-stones, or from those of a calcareous nature. Having also pounded grit-stones, in various ways, and caused them to be shaken together for a great length of time, I was not able, even then, to collect any sort of substance from the bottom of the boxes but simple dust.

This is a subject on which any person may easily try an experiment for himself, by rubbing two stones against each other between his hands, and observing the nature of the matter that will detach itself from their surface, however great may be the force of the friction. If, then, it may sometimes happen, that grit-stones, being decomposed, are reduced to the small grains of sand which formed their component parts, this will certainly arise from any other causes rather than collision and friction. The different actions of heat and cold, dilating and contracting variously their parts, the humidity of the air that has penetrated them, and other similar accidental causes, may sometimes separate and dissolve them. But sandstones, as we have already observed, are very rare in our rivers, and the combination of causes just mentioned must be still more so. Generally speak-

ing, the concussion and friction of the stones and gravels which are found in the beds of rivers, however great and however long continued they may be, can never form sands, and can only produce a very fine dust.

To set the present question finally at rest, I endeavoured to ascertain what quantity of dust could be obtained by simple friction, and what diminution takes place in stones and gravels; and to determine the point, I considered the space, and the time, of the friction.

To decide the time correctly, I selected forty river stones, white and gray, of various sizes, large and small: I caused them to be shaken in every direction, in a box of wood well closed, with the utmost force that could be applied by a man, at different intervals, for two hours together; after which, on collecting the dust found at the bottom of the box, with five little irregular pieces of stone, and adding the sediment I found in the water twenty-four hours after both the one and the other had been washed in it, I discovered only two ounces. The whole weight of the stones altogether having been five hundred and four ounces, it follows that it would have required an application of the same force for twenty-one days to produce an entire dissolution of the stones:—a term much longer than would be required for waters running at the rate of four or five miles an hour, as is the case at their surface, and with the still greater velocity which they have at the bottom, to transport the substances which they carry from the first springs of the rivers to the utmost limits of the gravels.

Next, to determine the space required, I caused two river stones to be ground on a grindstone, by

pressing their flattest parts with the greatest possible force against it. After 2200 turns of the stone, which gave about 4267 braces* as the space run over, the stones were a little flattened from about three inches in diameter, and had each lost about one twenty-fourth part of an inch in weight.

Whence it results, that, supposing stones to move at the bottom of rivers with a velocity equal to that of the grindstone, and the force of the friction in both cases to be the same, it would require, to the entire dissolution of stones ten or twelve ounces in weight, that they should pass through a far greater space than the whole length of our rivers.

One may, however, observe, that the force of concussion and of friction in the beds of rivers must be much less than that which is used in passing stones over the grindstone, or shaking them violently in boxes. The concussions of river stones with each other should be estimated by the relative velocity; that is, by the difference of the velocities with which they are carried along by the water. Sands, slime, and other earthy substances, which are almost always interposed between the stones, and even the water in which they swim, considerably diminish the action of the stones upon each other. Even the friction is very small, as Father Belgrado has demonstrated at great length in his elegant Dissertation on the Diminution of Stony Masses in Torrents and Rivers. He has observed, that stones, torn from the mountains, are precipitated down their declivities, turning, for the greater part of the time, on their own centres; that they continue to roll along in the same manner in the beds of torrents, until, the slopes becoming

* The *brace*, or *cubit*, of Milan, is about twenty English inches.

less, they afterwards slide along the bottom, rubbing against it, and are thrown here and there by the direction of the current, and the impetuosity of the waters. He then observes, that, during the whole time in which the stones descend rolling and turning round their centre of gravity, the projecting sharp points of some can hardly enter into and get entangled in the cavities and depressions of others; and thence it results that the friction is small. Lastly, he has remarked, that as the stones, in sliding along the bottom, present always the same surface in contact, the friction will then arise from the pressure, and the pressure again from the weight of the stones that scrape the bed, which can produce only a trifling effect, since river stones, generally speaking, are exceedingly light.

Father Grandi, in his "Considerations on the Dam of the Era," has discovered, by several experiments, that the specific gravities of the gravel in the water, and of the water itself, were nearly as five to three; whence he infers, that the transverse impetuosity of the waters was sometimes sufficient to raise the gravels from the bottom, and to throw them on the edges of the dikes, and even on the free-sides, and to the tops of their steepest embankments. Amontons has since asserted, that the resistance produced by the friction is equal to one-third of the weight; from which it appears, that the friction of river stones and gravels must, in every point of view, be very small.

The great difference which exists between the friction that stones naturally experience in the beds of rivers and that which is artificially produced by means of grindstones, or in boxes, being once established, no one can then possibly imagine, that gravels are

pulverised by the impetuosity of the stream, or that stones sensibly lose their weight. The most furious eruptions of stones are those which take place on the first great floods: even then, however, as the stones are descending from the sources of the rivers to the utmost limits of the gravels, neither time nor space sufficient is afforded greatly to reduce their original size. The action of the stones, which are set in motion three or four times in the year by the subsequent freshes, on the stones already deposited in the beds of the streams, must undoubtedly be considered as much less; and it is certain, that the friction of the stones on all those which they encounter, in running the whole length of the river, is far greater than that which can be experienced by any given number of other stones which run over them in the other freshes.

Very little effect is to be expected from that rising and general reversing, which Viviani has observed to take place in violent floods, from the nearest to the most distant places, from the right to the left, and from the surface to the bottom. The action of the waters, which strike the stones, and constantly impel them forward, ought not to be reckoned; for a small thread of water cannot experience any sensible resistance from the sharp edge of a stone, when struck obliquely. The hardness of river pebbles too is so great, that our highways in Lombardy, which are covered with these gravels and stones, though continually beaten by carts, carriages, and horses, have no discernible marks of wear, although these roads have been made a great number of years.

The low deep noise that is heard in rivers during great floods, not only in such as carry gravels, but

even when they bear along only sands and silt, marks the action of the water on the air, rather than on substances moved and tossed about on the bottom; for even if these substances rubbed against and crushed each other, they could not emit a sound to reach our ears, being covered with water to the depth of several feet.

It may with truth, then, be asserted, that the shock and mutual collision of stones with each other and with running water may well smooth, and sometimes polish them, and thus in some measure diminish their bulk, change their shape, and lessen their surface: a position which I never pretended to deny; but they can never reduce them to sand, or to powder; neither can they sensibly diminish their weight.

It is certain, that the constant friction which stones meet with in the beds of rivers, although it is insufficient to dissolve, or considerably lessen, either stones or gravels, may yet be adequate to render them smoother, and to give them a greater degree of polish. Stones that are rough and uneven may, by means of friction, more readily diminish in substance, because the angles and points of other stones, and, above all, sands, entering without obstacle into the small cavities of their surfaces, it requires to round and polish them only the application of a sufficient force to break off the small projections that constitute their roughness. But when the stones have acquired a certain degree of smoothness and polish, as they have then neither elevations nor hollows capable of admitting points and angles, a much greater power becomes requisite to introduce into their surface these very angles and points.

Upon this particular we may consult experience.

Take any piece of marble, provided it is rough and uneven, rub it hard with a stone and wet sand, or any other powder, with a determinate force, and for a given time, and a certain portion will be taken off, greater or less in proportion to the roughness and inequalities of the surface; but when once the marble is smooth and polished, a much greater time will be required to produce any sensible diminution in the solid mass.

Similar results might be deduced from the experiments, which we have related, of the stones passed over a grindstone; and it is the same with the other reflections which we have added. Whence it may be concluded, that the loss of substance in stones and gravels would be still smaller, if, for the friction on grindstones, which is termed *flattening*, were to be substituted that called *turning*, which occurs in the experiments made on stones shaken in boxes; and it is chiefly this sort of friction that stones meet with in rivers.

In polishing marble, glass, and other substances, with sand, it is observed, that the sand always becomes finer and finer in proportion to the continuance of the friction; so that sands, which at the commencement of the operation were very coarse, become by the end of it excessively fine and light. This arises from the different interjoinings of their parts, and their irregular shapes, by which their points and angles are more easily broken off, as well as by the action of the lever, which must not be overlooked, as far as regards the points most exposed and placed the farthest from the centre.

Thus we establish an important truth, that although there is not in the beds of rivers any force sufficient

sensibly to diminish the dimensions of the gravels, and to reduce them to powder, yet the continual motion is adequate to give increasing polish to the gravels, and to render the sands finer and finer as they pass along.

To recapitulate that which we have said above; round stones, gravels, and sands are original substances, torn from the mountains by the impetuosity of the streams, and carried down in the beds of rivers, Their quantity and distribution in every quarter of the globe, even in places where neither river nor torrent ever existed, evidently demonstrate that these substances were originally prepared and arranged by Nature. M. de Buffon, having observed, in his Natural History, Vol. I. Chap. vii., that round stones are found in different countries, on the surface, in the interior of the earth, and on the summits of mountains, as Leibnitz also has remarked in his Protogea, and as I have myself seen even in the first springs of rivers, has thence concluded, that their rotundity was the work of Nature. M. de Reaumur, in the "Memoirs of the Academy of Sciences for 1723," has drawn the same conclusion from the following observations which he has made:—that all stones have some degree of roundness, that their angles are all blunted, and that their transverse section is curvilineal, and returns into itself.

Thus, as it appears that the gravels of rivers are more smooth and better polished than those which are found spread over plains and mountains, and, moreover, that the sands which are progressively discovered in the lower beds of rivers are gradually of a finer texture, the entire effect of friction, and of the striking of these substances against each other, will

be a greater polish in the exterior of stones and gravels, and a greater fineness of the sands: that is, in the bosom of the mountains, where the falls are precipitous, and where the running waters detach and sweep down large quantities of stones, gravels, and sands, the stones and gravels reciprocally striking and rubbing each other with the sands with which they are mixed will become more polished and rounder; but the impetuosity and force of the waters decreasing with the fall, it will be only the smallest and bluntest stones that will follow the course of the rivers, and the points and angles of the sands that roll down along with them being no longer able to insinuate themselves into their surfaces, such stones cannot be reduced to sands, neither can they undergo any sensible diminution. In the sequel of their course, these stones, continually changing their situations with each other, and also with the uneven parts of the bottom, will acquire such a degree of resistance as the water will not be able to conquer; so that, without going further down, they will be fixed on the bottom, and become a part of the bed. Hence results the succession of stones always gradually less, and the conformation that is observed in the last limits of gravels; so that, in following the course of any river, you will pass from a bottom entirely covered with gravel to one where you will meet only with some pebbles dispersed here and there; after which, no more gravel will be met with, except in places where the waters are deeper and more rapid; and, lastly, sands only will be found, which, lessening by degrees in their dimensions, flow on, with the other turbid and muddy substances, to the sea.

CHAPTER III.

ON THE FIRST TRUNKS OF RIVERS AND TORRENTS.

THE question, which was discussed and decided in the last chapter, is not only interesting to philosophical curiosity and erudition, but also of essential importance, both in theory and in practice, to the scientific direction of rivers and torrents.

Guglielmini (Chap. v. Prop. vi.) when stating that stones and gravels, striking against each other in the beds of rivers, by their mutual friction sensibly reduced their substances, and by slow degrees were ground down to sands; assuming, at the same time, the whole of this operation of wearing down and dissolving the stones could take place in the space between the first springs of the river and the utmost limits of the gravels; was of opinion that, when fresh gravels came down, the river beds would not be raised, and that the whole quantity which was daily supplied would not be more than adequate to meet the consumption.

On the other hand, if the stones and gravels are not turned into sands, and do not reach the sea, but remain in the river beds as they have been carried down by the freshes, it will necessarily follow, that the beds of rivers that flow over gravels must continually be raised: and this is exactly conformable to the most careful observations. There is no person in

Tuscany that either disputes, or doubts, the increased elevation of the Arno, and of the other torrents. It was observed, in the visit of Riviera, that the Reno had raised its bed in the upper parts of its course; and it is a fact, that, a few years prior to this visit, the embankments of that stream were extended as far as the bridge on the Æmilian Way, though, at the visits of d'Adda and Barberini, they commenced only at the Church of Trebbo. The rising of the bed of the Crostolo, and of the Secchia, was also noticed at the visit of Rinuccini. In like manner, it was observed, that, from the year 1723 to 1761, the bottom of the Lavino had raised itself nearly four feet at the bridge on the road to S. Giovanni. All the bridges in Lombardy, the arches of which are either completely, or partially, obstructed, exhibit to every passenger the quantity of gravels which are there accumulated. At Pontremoli, where the Magra receives a great tributary stream, I have observed the remains of ancient houses below the ground-plan of those at present occupied.

Nevertheless, it is not correct to assert, as some persons have done, that if river stones were not by degrees converted into sands, and were not under this new form conveyed to the sea, the raising and filling up of the beds of the rivers would be so great, that the streams, flowing backwards, would inundate the low lands, and be turned out of their first channels. For, in the first place, running waters sweep down new gravels only in the first violent burstings of each particular flood; and, besides, the quantity of gravel so swept down is not so great as some have imagined. A considerable quantity also is used in the repairs of the roads, or for other purposes. It has been calcu-

lated, that there are annually taken out of the Reno 125,000 cubic feet of gravel merely to repair the highways. Hence rivers cannot, in general, raise their beds so as to overflow their banks, and to turn themselves out of their channels. But there sometimes happen cases, in which extraordinary quantities of gravel are brought down: and then, either the river must be secured between very high banks, as was done to the Ombrone; or the stream will be compelled to change its bed, as has actually happened to the Reno, to the Panaro, and to the Taro, and not unfrequently occurs in the higher branches of the Po, in those parts where the gravels are largest and the most plentiful. With respect to the lower channels, into which a less quantity of substances is brought, and where, of course, the bottom is not so perceptibly elevated, although it is always raised to a certain degree, it is useless to inquire what may befall them in length of time, and what may be the state or course of our rivers some centuries hence.

It is very certain, that, in places where the courses of rivers are impeded by rocks, or similar obstructions, or are crossed by some sluice, dam, or cataract, the whole bottom of the river is more elevated: because, as is well observed by Guglielmini (chap. xii.), the dam, or sluice, as soon as erected, by refusing a free passage to the water, and retarding its stream, facilitates the deposition of stones and gravels; and the bed of the river at the sluice being thus raised to the height of the sluice, causes a proportional heightening in the upper parts of the same bed. Of this circumstance we have a singular example in Florence, where the Arno, passing through the centre of that city, is enclosed between the two dams of St Nicholas

and dell' Uccello. Its bottom is raised to the top of this last mentioned mound. Viviani has demonstrated, in the six first paragraphs of his celebrated Discourse on the Arno, that the bottom of this river is continually rising, either from stones, or from gravels, or from sands, and even earth, as far as to its entrance into the sea. He has proved the assertion generally, by the loss of fall at the mills, by the filling up of the arches in the bridges, and by the increasing elevation of the beds of the tributary streams of the Bisenzio, and of the Ombrone, above the level of the country. He has, further, collected the several observations which he made in the space comprehended between the two dams, whether on the sewers, or the pavements, or the foundations of ancient edifices, by which the great rise in the bed of the river may easily be discerned.

The most important observation is, that, in the year 1677, Viviani, then intrusted with the repairs of a part of the foundations of the great palace of public offices, having brought forward towards the river the ancient windows of the vaults of the grand front, caused them to be walled up a brace* and a half higher, on the assurances given him by persons well acquainted with the spot, who declared that, in the great floods of the immediately preceding years, the water entering by these windows, which it had never done in the greatest floods of former seasons, compelled the removal of the horses from the stables, and, independently of the expense occasioned to clear out the mud and filth, rendered them at the same time so unhealthy that the horses were sick for several months. There is, however, every reason to believe,

* The *brace* or *cubit* of Florence is about 22 English inches.

that so celebrated an architect as Vasari, who, in 1560, planned and superintended this magnificent residence of magistracy, and particularly the grand front, which he himself asserted had its foundations laid on the river, and almost in the air, took the precaution to raise the windows to such a height, that, in his own time at least, the waters could not enter even at the highest floods.

Different schemes were formerly proposed to prevent the reflux and overflowing of the waters, and the other inconveniences which were occasioned by so great a rise in the bed of the Arno. These projects were collected and examined by Lupicini, in a discourse printed in 1591, and have lately been reproposed with various modifications: they may all be reduced in substance to three.

The first is, to diminish the height of the water in floods, by turning the stream of the Arno either wholly or partially from Florence, or by opening above this city a large drain to receive the superabundant waters in great freshes, and to return them into the river below the town. It may be objected against this plan, that to turn out of its ancient bed a river so large and so rapid as the Arno, is an experiment improper to be tried, or even to be proposed; and, that all the deflections that can be made in the streams of rivers do not serve to diminish the height of the waters in great floods, as we shall demonstrate at great length in the proper place.

The second scheme was, to raise the embankments of the Arno, and to close all the side-openings of the quays, taking means to procure other outlets for the sewers, lest the waters, if not prevented from flowing back through these openings, should commence by first inundating the lower parts, and then con-

tinuing to spread themselves through the city, should there occasion great damage. But, besides the very great difficulty of turning, or of reuniting, all the drains, and of closing such numerous openings, each of which would be sufficient in great floods to lay the town under water, several other obstacles present themselves. First, the raising the parapets one cubit, as last proposed, would occasion the loss of the fine view of the Arno, without securing the city from inundations in the time of very great floods; secondly, a considerable risk would always be run by thus enclosing an entire river to the height of its greatest possible rise, and keeping it as it were suspended in the air between two walls.

The third project was, to lower the bottom of the bed of the Arno throughout the whole space of its course through Florence, by entirely or partially destroying the dams. To this it was objected, that, besides depriving the city of the important convenience of the mills, whose water was supplied by means of these dams, it would be exposing the edifices near the river to an evident danger of being ruined, particularly the Bridge of the Holy Trinity, which is a masterpiece of architecture. It was assigned, as a foundation for these apprehensions, that in the great inundation which took place in 1333, as related by Villani, a part of the dell' Uccello Dam having been ruined, the stream tore up from its bottom so considerable a quantity of substances, that they swept away the two bridges of la Carraia and of the Holy Trinity. I, however, consider these fears as idle and groundless: because, in the first place, the ancient bridges at Florence had not the solidity and consistency with which they have been since rebuilt; and, in fact

there have been other occasions on which these bridges have been thrown down, although the dikes had not been destroyed. This was the case in the flood of 1557, which swept away the Bridge of the Holy Trinity, and a considerable portion of that of la Carraia, as is narrated in the Opuscules of l'Ammirato. But the new bridge of the Holy Trinity, built by the celebrated Ammanati, has its foundations laid so deeply and so substantially, that there is no reason to apprehend any sort of accident from the greatest floods. In the next place, the two cases are essentially different: in the one, the dam, destroyed in a high flood, opens a free and an unforeseen outlet to the waters, which it had retained, and caused to swell back on the parts above it; in the other, the dam, gradually lowered at the lowest ebbs, by affording free passage to the current, diminishes the rise of the floods, and renders them less dangerous.

I am therefore of opinion, that, in suffering the upper dam to remain for the convenience of the mills, and thereby retaining the greater part of the gravel above the city, one might, without risk, reduce the height of the lower; and, further, I consider this as the only mode of guarding against the damages and inconveniences occasioned by the filling up of the bed of the Arno. The lowering of the dam would bring with it that of the whole bottom of the river, and cut up by the roots all the possibility of the reflux and overflowings of the water. By lowering it only a few cubits, the city would be sufficiently secured; and the mill-race, which is derived from the dell' Uccello Dam, and which enters first into the Bisenzio and afterwards into the Arno, might still serve for the greater part of the year. In fine, other means might

be found to supply the lower mills, without exposing so beautiful, so rich, and so magnificent a city to frequent inundations.

But to return to the construction and mechanism of dams: it is certain, that, by throwing a dam across the bed of a river, the deposition of stones and gravels in the upper part is facilitated. But it is not true that by this means it is possible to retain the whole of them in the upper beds. It was under this erroneous impression, that, in the last century, they raised the mouth of the opening made in the torrent of la Nievole, above two-thirds of the rise of the great floods, with the intention of filling up some hollows by means of the deposits; but the event turned out quite contrary to the expectations formed, and, notwithstanding all the precautions that were taken, the gravels of this torrent passed over the mound.

Father Grandi, in his " New Considerations on the Construction of a Dam in the Era," has assigned it as a reason for this effect, that the stones, being raised from the bottom, and carried along to some height by the impetuosity of the waters, pass over the dams, and are precipitated below, although the bed of the river above the dams is not so elevated as the top of the dam; and in proof of this assertion, he quotes the instance of the Dam of Ripafratta, on the Serchio.

Guglielmini, chap. vii. and xii., had already observed, in general, that dams and sluices retain only a small portion of the stones that are brought down from the mountains—that is, so much only as is requisite to fill up the void formed by the height of the sluice, which once filled, the river begins afresh to establish its bottom, above the sluice, on the same slope which it had before, and resumes its former

tendency to carry down similar substances to those which it had formerly transported; and, therefore, that, if sluices were not elevated considerably above the bed of the river at first, and were not constantly raised afterwards, as Viviani has advised to be done in all the tributary streams of the Arno, it would be impossible to prevent the spilling of the gravels.

The above-mentioned Father Grandi, in his Considerations on the Dam of which we have just now been speaking, thought he could infer from some principles laid down by Guglielmini, that the bottom of the river must establish itself on a curve similar to that which it formerly had, which, beginning at the top of the dam would extend throughout the whole of the upper space, until it met some other dam, or a collection of rocks, or some other obstacle, either natural or artificial, by which the continuity of the bed was interrupted, and which might, for this reason, be considered as the *equivalent origin* of the trunk below it.

But the celebrated Bacciali, in the first part of the second volume of the "Acts of the Academy of Bologna," has very judiciously remarked, that if, by the opposition of a dam, all the bed of a river were equally raised as far as its first origin, it would follow, of course, that the bottoms of all its tributary streams, and those of the drains of the lands, would be raised in the same proportion; because the raised bed of the receiving river would be to them as so many other dams: which, however, is not substantiated by facts. In reality, the sluice of five feet, made in the Idice, has done no mischief to the neighbourhood; and the same has been the case with that in the Bisenzio. It is certain that, if the velocity of the current had no

other cause than its antecedent fall, it would be proper to assert, that, by opposing a dam to a stream, it would be compelled to adjust its new bed, backwards to its *origin* either *true* or *equivalent*, on a curve which would contain within itself all the numberless natural slopes of its ancient bottom, disposed nearly in the manner that Father Grandi mentions; because, as it is the property of all turbid rivers to have a fixed slope, when once this slope is diminished in any river (no matter from what cause), as soon as there is a flood it will regain that slope by means of its deposits, and raise its bed equally throughout the whole of the upper trunk. But in the particular case of dams, the waters, precipitated from the top, acquire a greater velocity; and those which fall, being themselves accelerated, accelerate also those which follow: and thus all the upper bed disposes itself into an ascending concavity, as Zandrini has observed in various rivers, and as I have myself seen, particularly at the famous Sluice of Casalecchio. Thence it arises, that rivers establish their bed on a less slope than they formerly had; and although it may so happen that these heightenings of the bed may reach to the very spring-head of the river, yet the bottom will never be raised in the upper parts so much as it will be near the dams.

Eustace Manfredi, in his " Opinion on the Dam of the Era," explained himself in similar terms, and said, that throughout the whole space, to which the acceleration of the stream flowing with a free fall extends, the river would run on a less slope than it would require if its bed were continuous; accordingly he asserts that the line of the new bottom above the dam should never be drawn, upwards, precisely from

the top of the dam, but only from the point where the aforesaid acceleration begins to be insensible, which point is necessarily lower than the parallel line of the old bottom, drawn from the top of the dam, although it be higher than the horizontal line drawn from the same summit.

To obtain some precise information on the distance to which the increase of velocity given to a river by a free fall is extended, we may consult one of the first engineers that Italy has produced. Barattieri, in the sixth chapter of his Sixth Book, has described the bed of the Stirone, at twelve stations, within the space of six miles, from the town of Saint-Donino to the Sluice, from which the waters descend with great velocity. According to the profile which he has left us, the surface of the stream falls greatly in the last half-mile above the Sluice; but a diminution of the body of the waters and a lessening of their height are discernible at the distance of two miles. Thus the acceleration of the stream actually extends considerably upwards, although the difference of the velocities, distinguishable by the eye by means of floating bodies, is to be observed only at a very small distance from the sluices. Similar observations have been made by Manfredi, in his "Notes on the Seventh Chapter of Guglielmini."

CHAPTER IV.

ON THE RECTIFICATION OF THE UPPER BEDS OF RIVERS.

The practical rules, which ought to be observed in the upper trunks of rivers, will differ, essentially, according to the various opinions that are formed of the nature and origin of the substances brought down by their streams. For if river stones, by constantly striking and rubbing against each other, wear away incessantly; if gravels are so reduced as to become smaller and smaller, until in the end they are turned into sand; and if all these operations can take place within the space comprised between the first springs of the river and the lowest limits of the gravels, then, in augmenting, no matter by what means, the force and rapidity of the waters, whether by uniting several streams, and thus increasing their height, or by shortening the distance they have to flow, and so increasing their fall, it might be expected that a greater portion of gravel would be dissolved, and carried down, together with the other sands, to the sea. On the other hand, if, from the mutual shocks and the friction, no visible diminution takes place; if the gravels are not pulverised and reduced to sands; and, if stones constantly remain stones, as we have already proved by so many arguments, experiments, and observations, no other result can possibly arise from increasing the fall, the volume, and the impetuosity

of the waters, but the compelling of the stream to carry its gravels farther in advance. But the same gravels will always remain at the bottom, and must soon heighten the lower parts of the bed, and at length also the higher; because fresh floods, loaded with new substances, which continue to descend on the lower plane of the rivers, already raised by the deposited gravel, will be compelled to slacken their current, before increased by the augmentation of the preceding fall, and being now unable to throw forward the weight with which they are loaded, will permit it to sink to the bottom: by which means the fresh sands, and the fresh gravels, mixing with those formerly brought down and deposited at these places, will constantly raise them more and more; and the fresh accumulations made in the lower parts will serve as a support to those that follow, which will therefore remain in the upper bed.

In 1718, Manfredi, being consulted upon a rectification proposed to be made in the Reno, at a place where it flows over gravel, in a written report entirely disapproved of the measure, assigning two different reasons in support of his opinion. The first was, that rivers, which carry gravel, do not generally accommodate themselves to the roads it is wished to compel them to take; and that, when they do so for a time, they shortly after quit them, and make themselves new beds, thereby rendering useless all the efforts of art, and all the expenses incurred to restrain them. It is well ascertained that rivers whose bottoms are gravelly, at every new flood make new deposits, irregularly, here and there, which, changing the surface of the bed, compel the thread of the stream to alter its course and situation. It is for

this reason that gravelly rivers with difficulty submit to restraint, or to a course assigned to them; and this is the reason why it frequently happens that rectifications and cuts made in them do not succeed, contrary to what happens to streams flowing over sands, which, although they do not always preserve the same state, still change less and for a shorter distance; and as it seldom happens that their bottom and the current of their stream are changed, their courses are, on this account, more easily restrained and regulated.

The other reason assigned by Manfredi is, that where a river is straightened and its course is considerably shortened, although there ought to result a proportional abasement of its upper bed, this good effect will be destroyed by the gravels, which will be pushed further on, and will raise the bed below the cut. According to what has been already said on the origin and nature of river substances, it may with certainty be predicted that, by shortening the course of the river, there will follow an extension of the gravels and a greater elevation of the bed, first in the parts below the cut, and afterwards in all the upper channel.

Thus, straightenings and new cuts, which produce excellent effects in streams carrying substances of little grossness, can only injure the beds of those which transport gravel.

For a decisive example, let us return to the river Arno. Viviani, after having demonstrated the considerable and constant heightening of the bed of this stream, pointed out the system proper to be adopted for its regulation. He proposed, first, to reduce the great slope of the side valleys nearest the Arno, by

placing and constructing in them several sluices or traverses, at-distances proportioned to each other, faced with good walls built with lime and sand, pierced with several tunnels, having substantial broad foundations, and a considerable outer slope, with raised ways at the foot, and several projections or steps in those places where it might be requisite, from time to time, to carry them up to a greater height, after they had been reinforced behind by the substances that might have been brought down and deposited by the water. Secondly, he advised planting in these valleys, above the sluices, very thick plantations of such trees as were suitable to the localities and the nature of the soil, for the space of 300 braces, and even more if it could be effected. Where the bottom was rocky, and nothing could be produced to repay the expense of making such sluices, and no plantation of any kind could be formed to retain the matters brought down by the impetuosity of the stream, Viviani recommended to select in the lowest spot a convenient, level space, of the least valuable quality, and to surround it with an embankment, to serve as a cesspool, where these substances might be conveniently deposited. Thirdly, he proposed to reduce the excessive fall of the Arno, below the Incisa, by re-establishing some ancient dikes and constructing some new ones, and to make a similar rampart of dikes across the bed of the Sieve, at some distance from its opening into the Arno, as well as at the entrances of the other small rivers and brooks that flow into it. On the whole, Viviani laid it down as a first principle, that it was requisite to traverse and obstruct the course of the Arno, in whatever way it could be effected, and to compel this river, as much

as possible, to leave its large gravels and stones in its upper beds.

A desire to establish a more commodious navigation on this river, and to obtain the lands occupied by its greatest sinuosities, occasioned the adoption of a diametrically opposite plan. Several large masses, which traversed the bed of the Arno, and served as natural dams, were removed. They then narrowed and straightened the bed of the river above Florence, and converted it into a canal from Florence to Signa. Its course was shortened near three miles above the city and one mile below it. I will not mention the expense of all these works, but point out the consequences. Above Florence the Arno has quitted in some places the rectilinear bed newly made to contain it, and is retained in it in other places only by very large stone dikes, that are exceedingly expensive. Within the space where it divides the city, although the bed is contained between two fixed boundaries—that is, between the two dams—its bottom is, notwithstanding, considerably raised since the time of Viviani. The fishermen, also, unanimously declare, that within the last years, the fishery formerly carried on in the small bays and deepest concavities of the river has been nearly lost. Besides, prior to these changes, the stones in the Arno, constantly lessening in size below Florence, used to cease at the Abbey of Settimo; so that from this abbey, in going down the stream, as Viviani has particularly remarked in the beginning of his discourse, not a stone was to be found on the shoals along the shore. At present, from Florence to the bridge at Signa, which is three miles below the Abbey of Settimo, the Arno continues to carry gravels and stones. Beyond

the Ombrone and the Bisenzio, a sandbank, 900 feet in length, is observed, in which stones as large as the cones of the fir-tree are found. Below the Bridge of Signa, on the left hand, there is another shoal of large gravel thrown up; and in going towards the mouth of the Ombrone, several smaller sized gravels are found as far as Golfolina. It is, however, a fact that neither the Ombrone nor the Bisenzio carries gravels into the Arno. The shortening, then, of the course of this river for four miles has caused a continued prolongation of stones and gravel for the distance of three miles.

The extension of the gravel beds must necessarily elevate the bottom of a river. In fact, several of the arches of the Bridge at Signa are almost buried in the deposited gravel: some others have scarcely their imposts above the level of the bottom; and the highest raised arches are entirely under water in the time of floods. A small iron ring, which is fastened with lead into the right hand pier of the centre arch, may serve as a measure to determine the whole rise. Several creditable persons have assured me that fifty years ago this little instrument stood so high that the boatmen were obliged to go on the poops of their vessels to reach it: at present the circle of the ring touches the bottom of the river, of which the surface is level enough underneath the bridge. The bed must, therefore, have raised itself five or six Florence cubits at this spot since the straightenings were made in the banks of the Arno.

On the other side, it is fair to state, that a considerable portion of this rise ought to be attributed to the obstructions occasioned by the irregular figure of the bridge, the arches of which are too narrow,

and even not placed in one straight line, but rather in two lines inclined so as to form a perceptible angle. The elevation of the bottom below the bridge is considerably less; and, but for the obstruction of the arches, there would not have been so considerable an accumulation of gravels at this place; but, instead of this, they would have been impelled beyond the limits to which they are at present confined, and would have additionally raised the bottom in parts farther down.

Generally speaking, gravels will be pushed farther forwards in straight rivers than in those that wind; and these gravels, being deposited on the bottom at the greatest distances, will gradually raise, first, the lower parts, and at length those higher up. This heightening will be still greater if beds that have been made straight, and are by any means enclosed, should happen to cross any tributary streams, where they carry gravel or other ponderous substances; because, in this way, both the waters and the deposits of several separate streams will be united in one bed; and so the condition of the rivers will become worse and worse. The inevitable consequences of the rise in the bottom will be a greater height of the waters in floods, a difficulty in procuring a vent for the inundations of the lower countries adjoining, and the necessity of repeatedly raising and strengthening the embankments. Thus the rules for uniting rivers, and for maintaining them within straight embankments, with convenient slopes, although generally applicable to all such streams as carry sands through plains of little declivity, cannot be applied to rivers carrying gravels; and the best that can be done in such cases is to leave them as they are, separate and winding.

It would even be better to interrupt their course by throwing dikes or weirs across them, as Viviani has advised, thereby to retain the gravels as much as possible in their upper beds.

Although Guglielmini had formed other ideas on the nature of river substances, he nevertheless constantly concurred in the above opinion respecting the rectification and union of rivers and torrents, in those parts where they still carry gravels; regarding it as a very difficult undertaking, and one of which the ultimate success was exceedingly uncertain. In the Fifth Proposition of the ninth chapter, he has left us two general practical rules: the first, never to introduce the stream of any river carrying gravels into the bed of a great river with a sandy or muddy bottom: the second, never to shorten the course of streams which carry stones nearly to their own mouths. The application of these rules will appear in the following chapter.

CHAPTER V.

ON THE FORMATION OF THE UPPER BEDS OF RIVERS.

When it is required to straighten the course of a river, to change its openings, or in any mode whatever to unite torrents and rivers, the new bed should in all cases pass below the very utmost limits of the gravels. It is necessary to study Nature, and to seek by art to imitate her. Nature sometimes unites torrents in the midst of the rocks and precipices of the mountains; but in the centre of great valleys and fertile plains she never unites torrents, while they carry gravels, with other rivers that carry only sands and mud. We need not seek at a distance for the proof of this proposition; an example is exhibited in our great Valley of Lombardy, through the middle of which flows the Po, which, after it has ceased to carry the gravels of its own bed, receives none of any sort from its tributary streams, as Guglielmini has observed in the passage which we last quoted. This accurate observer of rivers adds, that the Po, after wandering in the neighbourhood of the Apennines, denominated Euganean by ancient historians, and after having been tossed hither and thither by the gravelly deposits of its own tributary streams, begins to flow in a settled bed only from the period that, having ceased to carry on its gravels, it receives from its tributaries none but sandy substances. Thus

Nature operates. We might cite many other examples of rivers that have formed fixed beds for themselves much nearer to the mountains. The Reno, amidst the Apennines, receives large stones from the Limentora, from the Orsigna, and other torrents; but after it has expanded itself in the plains, and has left its gravels, it receives the Samoggia, which also in like manner receives the Lavino, in situations where none but sandy substances are to be discovered. The Arno, below Empoli, and the Tiber below the place called della Capannaccia, have no gravels in their beds, and receive none from any of their tributaries. It is very evident that, if any river, after having relinquished its gravels, received others from some influent stream, it would not, according to what has been laid down, immediately have a fixed bed; nor would it finally establish one until it had reached those parts where it no longer received gravel of any sort.

Let us pause a little to consider the particular case of the Reno. Guglielmini has left it in his Writings, p. 353, that in his time the gravels of the Reno extended five miles below the Sluice of Casalecchio, that is, as far as the church called del Trebbo; and that, in more ancient times, the gravels reached much further down. It is unnecessary to search for the cause of this prolongation of the gravels at different periods of time: perhaps, in the days of Guglielmini, the bottom of the lower valleys having been heightened and rendered incapable of receiving the Reno, the course of the river had become less free, and consequently it had not sufficient strength to throw its gravels further on. Since that time, the Reno has been straightened by means of a cut made for about

two miles, a little below the last limit of its gravels; and it has opened itself new breaches in its banks, constantly nearer and nearer to Bologna. In this manner they have restored the ancient tendency of this stream to carry its gravels to greater distances. Be this as it may, it is a fact, that, for near a mile below the Church of Trebbo, the bed of the Reno is at present covered with gravels, stones, and large flints; that, in going lower down, other beds of gravel, covered over with sand and earth, are found at intervals till below a place called Malacappa; and that the peasants go with carts below Longara, to take up gravel for the repair of the roads, a certain sign that these gravels are large enough, and in sufficient quantity, to justify the assertion that the Reno flows there over gravel. That no doubt of the fact might remain, I verified it myself, in company with several other persons, and heard the evidence of the most experienced of the peasantry. In the Samoggia and in the Lavino, the gravels extend but a short distance from their junction; and they arrive there in such large quantities that the beds of both these rivers are considerably heightened. In the Idice, gravels and stones are found below the place called della Mezzolara; and the peasants assured me that, when they took it to repair the highways, out of one load of sand and gravel they generally found a third, or at least a fourth part, pure gravel. I learnt, for certain, from the farmers, that in the torrent Centonara the gravels reached as far as La Madonna, called della Rondanina, and that in the Quaderna they reached to within two miles of the mouth of the Gaiana.

I have dwelt on these facts to support and give weight to a decisive objection made against an ancient

scheme, reproposed with some alterations in 1760—viz., to cut the Lavino and the Samoggia above their confluence, and to cause them to enter into the Reno at Longara, turning at this place all the waters of the Reno by means of a new bed, which should run straight to meet the Primaro at Saint Albert, and collect, in its way, all the other torrents and drainings of the Bolognese. I asserted that this new bed would cut all the torrents of the Bolognese, in places where they carry large and small gravels; and, taking it for granted that it had the necessary fall, that the gravels of the Samoggia would reach to the Lavino, and those of the Lavino would enter the Reno; that the gravels of the lower torrents, assisted by the strength of the united waters, would be forced further on; that there was no reason to expect that the greater fall of the new bed could occasion any sensible diminution in the quantity or the size of these gravels; and that their continual deposition would be followed by a raising of the bottom, greater danger of ruptures in the banks, and greater difficulty in draining the lands. These were the principal reasons which led to the abandonment of the plan for this new bed; and it has since been proposed to keep lower down, and to form a new channel for the waters of the Bolognese, beginning the deflection of the Samoggia below its confluence with the Lavino, and that of the Reno below Malacappa.

It would be useless to repeat all the particular objections started against the line of Longara, which principally affected the dimensions necessary to be given to the new bed, to the free-borders,* and to the

* The *free-borders*, or *free-sides*, are open spaces, sloping, or horizontal, interposed between the ordinary limit of the waters and the em-

embankments, the outlets that would be required to drain the redundant waters on the low lands, the sluices, the subterranean tunnels, the excavations, and the method of conducting the works in making them. However, it will not be improper to restate here the other general difficulties which concern the first theories of rivers, and which may serve as examples in similar cases.

Guglielmini (in chap. xiv. of his work) has laid it down as a general rule, that the success of cuts made for rivers flowing over gravels is very uncertain; and has assigned for it those reasons which we before explained, and which experience has always justified, according to what has happened in the cut made in the Doria above Turin. Guglielmini afterwards treats of new beds to be given to rivers. Beginning with the case of a river which it is required to conduct to its termination, without any mixture of fresh streams, he says the undertaking will not be difficult provided the fall of the new channel be not less than that of the old one. This is precisely the case successfully executed in the Ronco near Ravenna, below the confluence of the Montone. Guglielmini speaks afterwards of new beds destined to receive several rivers: and he states, that if the streams which it is required to unite all carry substances homogeneous, such as sands; if there be sufficient fall and strength to carry these on to their utmost limits; and, further, if the new cut can be enclosed in the plane of the country, the success of the undertaking will be sure. This

bankments or dikes, which are to confine them in floods. In the Italian practice, they are found on one side only, or on both, and are of greater or less extent, as the localities, risings of the floods, and other circumstances appear to require.

will be the case with the Benedictine Canal, whenever it shall be completed. Guglielmini concludes by saying, that the case that would be the most replete with obstacles is that in which some of the tributary streams float down more ponderous substances than are carried by the principal river at the point of their junction. He asserts, that such a work cannot be attempted with any certainty of success, unless where the fall is uncommonly great, and the level surface of the country is exceedingly high. This is precisely the case in the proposed line of Longara, which, contrary to the exception above stated, would, for a considerable space, have risen higher than the level of the country, of which the slope or fall could not possibly have been excessively great, and in which the Indice and the Lavino, for example, would have conveyed to the point of their junction much more weighty substances than those of the Samoggia and of the Savena.

By making another exception to the theory of Guglielmini, we shall render more general the practical rules which he has taught us. The height of the fall can never obviate the mischievous consequences resulting from the union and straightening of rivers whilst still flowing over their gravels; for, by increasing the fall, the body, and the impetuosity of the waters, you can only force the gravels farther forward; they will still remain in the river, continually heightening and filling it up. In proof of this assertion, let us return again to the Arno, whose fall is certainly considerable from Florence to the bridge at Signa, since it is at the rate of upwards of three braces per mile. Viviani considered it too great in his days: since which, by shortening the channel one

mile, the fall of the river has been augmented; from whence no other effect has resulted but a prolongation of the gravels for some miles lower, and a greater elevation of the bottom. It is then true, generally speaking, that the canals, the unions, and the straightenings of such rivers as carry weighty substances, are undertakings replete with risk and difficulty. Guglielmini acknowledges, in chapter xiv. already quoted, that we have no certain rules for these sorts of works; and that the method of commencing the new canal lower down than the junction of the last tributaries, proceeding gradually, and carefully observing every circumstance that happened, could throw at the most but an obscure light on so difficult a subject. But he speaks in much stronger terms, in the writings inserted in the second volume of the "Florentine Collection," whilst examining a scheme for the formation of a new bed for the Reno, in length about forty miles. He there says, generally, that even if the country were sufficiently raised to admit of the waters being constantly and in all parts enclosed in excavations, it would still be working in the dark to persist in such an enterprise, for several reasons; and, principally, because there is no example existing by which one might be guided in planning and executing the works."* Eustace Manfredi has repeated the same objection in his Abridgment; and, in fact, the derivation from the Mincio of the Philistine Canal into the Po, made by Quintus Curius Hostilius, the outlet opened by Claudius from the Lake Celano into the Garigliano, the reuniting of the waters of the Po into one bed near Placentia, effected by Scaurus, the derivation of the Sile and of the other affluents into the

* A futile reason, calculated to prevent all improvement.

Laguna of Venice,* and other undertakings of a similar nature, although very great and very expensive, cannot be compared with the project for the derivation of the Reno and the other Bolognese torrents.

Eustace Manfredi, in the Abridgment already cited, adds another objection; which is, that the river, taken in flank by so many mouths of its tributary streams, would turn upon the opposite shores, enter the walling of the dikes, and infallibly lengthen its line; that there is no river whose bed is straight for so many miles, nor even whose bed, for so long a space, is composed of two or three straight trunks; and that this lengthening would probably be one-half, or at least one-third, of the whole length of the bed. Indeed, all geography does not furnish us with one example of a river of this nature, which, during a course of so many miles, flows always straight, and without making considerable windings. The course of streams bringing down light substances, such as sands and earth, may be shortened, cut, and made to flow in a straight line. We have in the Reno itself, and in several other Italian rivers, examples of similar rectifications, which have been perfectly successful, and that for the reasons already alleged; namely, because the bottom and the thread of the stream experience very little change. But rivers that carry gravels, as we have asserted in the commencement of the preceding chapter, very often amass them irregularly in various parts of their beds, and form heaps that force the current to bend from the one side to the other, where, if it meet with substances opposing less resistance, it forms new erosions; so that, by the constant action and reaction of the waters, the whole bed

* Venezia e le sue Lagune, 4t. 4to, 1847.

of the river is formed into a continuation of concave and convex curves. Thus, it is impossible by human art so to encase between embankments a river carrying heavy substances itself, and receiving them from several tributary streams at different levels, and by floods which come down at different times, that the river shall not serpentise, and materially elongate its course. By means of this elongation, it will happen, even when the fall and the slope of the new bed are at first sufficient for the stream to convey to the sea all the turbids incorporated with it, that in length of time they will be insufficient to prevent deposits and accumulations in the bed.

But as to what concerns the sufficiency of the fall, several other important considerations arise. In the first exposition of the project in question, as it was shown from the ancient levels, that the bottom of the Reno, at Longara, was raised seventy-two feet* above the bed of the Primaro, towards the entrance of the Santerno, this fall was considered as more than sufficient, if it were gradually distributed; first, at the rate of three feet per mile, afterwards of two and a half, and so on, constantly diminishing. But to convey water from one place to another, it is necessary to consider not merely the difference of fall between the two extreme points; for though the whole fall may be sufficient, it is still necessary to examine further, in what proportion the slope of the country diminishes in all the intermediate space; and here may arise two different and opposite cases, as the slope of the lower lands may be either greater or less than may be required. In the former case, very great excavations would become necessary, that the tribu-

* The Bologna foot is very nearly 14½ English inches.

tary streams might be made to fall from very high dikes placed at their mouths. In the latter, the river must be sustained as if it were in the air; the drainings of the country could not be made to enter it; and, in the event of a rupture, it would be impossible to repair the banks. According to the old and the new levels, the projected line for diverting the Reno at Longara would in several places encounter both of these difficulties. In some places, the whole of the new bed must be buried, so to speak, in the earth, and the Savena and the Idice must enter it over very high wears. In other parts, the new bed would be raised above the level of the country; and though it is true that there would be some drainings which might be made to enter it by turning them and giving them a vent lower down, yet there are others for which there would be no other expedient but the making of as many subterraneous tunnels, which, from their multiplicity and dimensions, must always be highly expensive, and of which the successful execution would be ever very uncertain. But of this enough.

BOOK II.

ON THE VELOCITIES AND SLOPES OF RIVERS.

CHAPTER I.

OF THE VELOCITY WITH WHICH WATER FLOWS OUT OF VESSELS.

It is a principle well known, and as ancient as Hydraulics, that the velocity with which water flows out of openings made in any sort of vessels whatever is generally greater in proportion to the height of the fluid contained in the vessels. Julius Frontinus has clearly stated this law in his Treatise on the Aqueducts of Rome. The difficulty was to find in what ratio to the heights the velocities should always vary.

Benedict Castelli, in his Second Book on the Measurement of Running Waters, having begun with inquiring in what proportion the velocity arising from the pressure of the upper parts increases, suspected that this very proportion was directly as the number of the pressing particles; or, in other words, simply as the height. But Castelli not being able to solve all his own doubts on the subject, either by the con-

jectures which he had himself formed, or by those communicated to him in some letters by Cavalieri, left it to others to pursue these researches more successfully than he himself had done. Torricelli, at the end of his Second Book on the Motion of Heavy Bodies, has established, rather by means of some physical experiments than by his mechanical conjectures, that the velocities arising from the pressure are as the square roots of the heights; and he has assigned to Maggiotti the merit of having been the first to attempt decisive experiments on this subject.

Torricelli commences his demonstration with a fixed principle in hydrostatics, that, if you apply to openings made in the sides of any vessel as many tubes, the water will rise in them to the same horizontal level with the superficies of that contained in the vessel. He then lays down two suppositions: the first, that the velocity with which the water begins to enter the tubes is all that is requisite to enable it to ascend through a height equal to that of the fluid in the vessel above the aperture: the second, that the water flows with the same velocity through the openings in the vessel, whether the tubes are applied or removed. He has easily inferred from these principles that the water flows through the apertures with the velocity which it would acquire in falling through the whole height of the surface above them, which is consequently as the square root of the height itself. But it is easy to perceive that these two postulates are equivalent to the theorem to be demonstrated: thus the demonstration is merely a simple begging of the question. The other principle, established in Huygens' Mechanics and by Daniel Bernoulli, of the equality between the potential descent

and ascent of bodies, falls into the same suppositions as those laid down by Torricelli, as far as it is applicable to running waters. Varignon, in the Memoirs of the Academy of Sciences at Paris, Ann. 1703, and Hermann, in the ninth chapter of the Second Book of his Phoronomy, have spoken on this subject in a very indefinite manner, asserting that the pressure in the vessels is in proportion to the height,—that the quantity of motion in the water which flows out of the holes is in proportion to the pressure,—that the number of particles which issue in a given time is in proportion to their velocity; and that, consequently, the height is perhaps as the square of the velocity. At the utmost, it is possible to apply these principles to the particles that first flow, but not to the others that follow after the whole fluid is in motion.

Newton, in the thirty-sixth Proposition of the Second Book of his Principia, desirous of determining the motion of water flowing out of a hole made in the bottom of a vessel, has begun by a different hypothesis; which is, that each particle of the water has really descended through the whole height of the fluid above it. This he supposes to happen in such a manner that the water round the hole remains motionless, precisely as if it were frozen; and that the water above the hole descends by degrees in the shape of a funnel, closing gradually from the superior section of the vessel until it reaches the section of the hole itself, thus describing a sort of cataract; adding, moreover, to these suppositions another, that all the layers or sheets of water, passing from the surface to the bottom, and growing thicker as they diminish in their diameter, remain parallel between

themselves. Newton determined, with his usual sublimity and elegance, the figure of the cataract and the other laws of the motion; and, above all, that the velocity of each particle of water in the hole is in proportion to the square of the height. He afterwards observes that, on account of the obliquity of the directions, and the motions with which the particles reach the section of the hole, both in the centre and in the sides, it so happens that they approach still nearer to each other in the opening, and that they are reduced, a little below the hole, to a narrower section, which he terms the *contracted vein.*

To ascertain the contraction of the vein, which arises from the simple convergence of the motions, without including the lessening of the diameter, which, in all vertical falls, arises from the acceleration of the fall, this great man contrived to make the hole on one side of the vessel, so that the water began to flow horizontally. The hole was circular, and five-eighths of an inch in diameter; it was cut also in a very thin even plate. In letting out the water, Newton discovered that the diameter of the vein, at the distance of about half an inch from the hole, was, to the diameter of the hole itself, nearly as 21 to 25. Now, as the velocity of the water which passes through the different sections is reciprocally as the area of the sections, or reciprocally as the squares of their diameters, the ratio of the velocity in the two sections of the hole and of the contracted vein ought to be that of the square of 21 to the square of 25, or simply as 441 is to 625, or as 1 to $1\frac{2}{5}$, which is nearly in the proportion of 1 to $\sqrt{2}$. Thus, by considering the contracted vein as the last section of water that flows out of the vessel, and by proving that the abso-

lute velocity is that which it would acquire in falling through the whole height, the velocity of the water in the hole will be in reality proportional to the square root of the height, but in its quantity it will only be that which it would acquire in falling through the half of that height.

These investigations are too ingenious and too celebrated to permit the memory of them to be lost; and they have since engaged the attention of the most illustrious mathematicians, John and Daniel Bernoulli, MacLaurin, Father Grandi, the Marquis Poleni, and several others. Daniel Bernoulli having thrown coloured powders into the water, observed that as these powders descended with the water, they formed a cataract very different from that which had been determined by Newton, which ought to be an hyperbole of the fourth degree. He discovered, it is true, the same proportion between the diameters of the contracted vein and of the hole; but all the other circumstances of the motion appeared to him to be different, as may be seen in paragraph third of the Fourth Part of his Treatise on Hydrodynamics.

The Marquis Poleni has found by some other experiments that the diameter of the contracted vein is to the diameter of the hole as $20\frac{1}{2}$ is to 26. Several other authors, and principally John Bernoulli in his Hydraulics, have started different objections to the whole theory of Newton. The principal difficulty is, that this theory rests upon suppositions which perhaps do not exist in nature, and of which, even when they might prove true in particular cases, it would not be less difficult to demonstrate the reality than to solve all the other problems that might be proposed on the motions of fluids.

The investigations of Newton have been more extensively pursued by MacLaurin in the twelfth chapter of his great work on Fluxions; but he has always involved his hydraulic theories in some arbitrary suppositions; as, for example, the distribution and division of the total weight of the fluid into three parts; of which one is destined to accelerate the motion of the fluid within the vessel, another to accelerate it in the orifice, and, lastly, the third to press the bottom of the vessel. John Bernoulli, desiring to substitute a new theory of hydraulics for that of Newton, has exchanged his suppositions for some others; as, for instance, that the whole weight of the fluid is employed in the acceleration of all its particles; and that the velocity of the particles, even in passing from the greatest to the smallest sections, arises solely from their weight. M. d'Alembert, in a new, sublime, and general theory which he has published on the resistance of fluids, has ably solved the doubts and difficulties that may arise from the theories of Newton, MacLaurin, and Bernoulli; and he observes, in general, that all that can be said on this subject is limited to two hypotheses: the first, that the different stratums of the fluid always preserve their parallelism, even whilst in motion; the second, that the velocity is equal and parallel to the axis of the vessel in all the particles which compose the same stratum. On this subject reference may be made to the Treatise on Hydrostatics by the celebrated Father Lecchi, in which he has ably removed the uncertainty of the mathematical demonstrations hitherto given on the laws of motion in waters which issue from vessels, or which flow in the beds of rivers.

One single reflection is sufficient to show that all

hydraulic problems are beyond the reach of geometry and of calculus. The difficulty of all problems is increased in proportion to the number of the conditions, of the cases, and of the differences which are stated. Thus, mechanical problems become so much the more complicated as the number of the bodies whose motions are sought, and which act in any way on each other, is augmented. But the first and most essential property of fluids is, that in them the pressure is extended on all sides, that their particles yield immediately to any force impressed, and that in yielding they mix readily together. Then, in a fluid mass, which moves in a tube, or in a canal, the number of bodies acting together is infinite; whence it follows, that to determine the motion of each body is a problem depending upon an infinity of equations, and which it is of course beyond all the powers of algebra to reach. For this reason, I consider hydraulics and hydrometry rather as a part of physics than of mathematics, or as a branch of mathematical learning in which the progress hitherto made, and that which shall be made hereafter, is purely hypothetical, and limited to certain cases which possibly never exist in nature.

As it is my intention to unite in the present treatise all that can be useful in the direction of rivers, I expressly renounce all hypothetical calculations and demonstrations, in which several authors, and especially Zendrini, have involved this subject; and, instead of this method, I have collected all the experiments, observations, and reflections, which can throw any light upon the most important cases.

We are assured, from physical experiments, that the velocities of water running out of vessels through

openings are very nearly proportional to the square roots of the heights. Guglielmini was the first to recommence in detail, and with greater precision, the experiments of Maggiotti and of Torricelli; for, having taken a vessel full of water, four feet in height, in the side of which he had bored sixteen circular holes, one inch in diameter, each of which could be opened whilst the others remained closed, and having opened them by degrees, one after another, he observed that the quantity of water which flowed out in an equal space of time, and consequently the velocity with which it flowed out of the apertures, in six experiments, was very nearly in proportion to the square roots of the heights. In eight other experiments it deviated from this law only by about a hundredth part; another time the difference was $\frac{1}{56}$; and again, $\frac{1}{32}$ part.

Mariotte, Poleni, and several other authors, have discovered that this law approached the nearer to the truth, the more carefully and exactly the experiments and observations were repeated. In the whole course of the experiments on this subject, those made by M. Michelotti a few years since in the neighbourhood of Turin, and which are described at full length in his Treatise on the Measurement of Running Waters, deserve particularly to be recorded and preserved for their multiplicity and precision. They completely prove that the velocities of the water are actually as the squares of the heights of the columns of pressure, and that all the differences usually discovered in experiments, are to be ascribed to the resistance of the lips of the openings, and to other fortuitous causes.

This principle once established, if the height of the water and the figure of the openings are given, it becomes a matter of pure calculation to discover the

quantities of water that will flow out in a given time. Guglielmini and Grandi have left us several theorems on this subject, and I have added another at the end of the second chapter of the First Book on the Laws of Gravity. If the figure of the aperture is first of all a square, which on one side touches the surface of the water at rest in the vessel; next, a circle inscribed in that square; then, a triangle also inscribed, first with the vertex up, afterwards with the vertex down; and lastly, a triangle having the same height and vertex as the other, but only half its base; the quantities of water that will flow out in equal times, in these five different cases, will be successively as 5, 4, 3, 2, 1. In the case of a square opening, such as is commonly made to let out water, all the difficulty of the distribution is reduced to squaring the segment of a parabola, of which the axis is vertical, the vertex in the surface of the water at rest, and the height of the segment equal to the height of the opening. The parabolic table of Father Grandi saves the labour of a simply arithmetical calculation. The experiment reported by Mariotte in his First Discourse on the Motion of Waters, proves, that through a circular hole of an inch in diameter, mersed constantly one line below the surface of the water, there flow out, in one minute, $13\frac{3}{8}$ pints, Paris measure, making $25\frac{84}{100}$ French pounds.* This experiment is sufficient for calculating the absolute quantity of water that can

* The Paris pint is usually estimated to contain 2 pounds, or nearly 2 pounds, of water. The author considers the weight of the pint of water to be to the pound as 1·932 is to 1; and, consequently, $13\frac{3}{8}$ pints to be equal to 25·84 pounds, or 25 pounds and very nearly $13\frac{1}{2}$ ounces. As to the quantity of efflux itself, Bossuet, having conducted the experiment with very great accuracy, states, Hydrodynamics, § 853, that, in the circumstances above described, it is $13\frac{1}{7}$ pints.

issue in a given time through a given opening. It remains now to show how the principle applies to the most interesting of all cases—the total quantity of water discharged by rivers.

CHAPTER II.

ON THE VELOCITIES OF SINGLE RIVERS.

The velocity of a river, which flows single, without receiving any other streams, and which is swelled solely by the waters of its springs, or by rains, depends either on its fall, or on the pressure of its upper parts. All the particles of a fluid, in descending an inclined plane, are accelerated by the very same laws by which all other ponderous bodies are accelerated. The acceleration that arises from pressure belongs properly and peculiarly to fluids, which, as being composed of detached particles, yield to all forces impressed on them, and are thereby put in motion. The slope of the bottom contributes principally to the acceleration of the streams in the primary beds, in the bosom of the mountains, where the height of the body of water is very small, and where the fall is very rapid. The pressure of the higher parts contributes principally to quicken the current in the midst of great plains, where the inclination of the bottom is very small, and where the body of water is much increased. The rapidity arising from pressure, in streams that are enlarged in the plains, is sometimes greater than that which is caused by the slope in mountainous places. Zendrini has observed, in his tenth chapter, that the Po, in its lower parts, acquires, from the increase of its body of water, a much greater

velocity than it had when it quitted its gravels in its higher districts, and that this swiftness was so great, that it would have sufficed to carry on the gravels, if they could have passed through the intermediate space, and could have reached the place where the augmented body of water begins to counterbalance the constantly increasing loss of force occasioned by the diminution of the fall.

In the intermediate beds of rivers, both these reasons may contribute to the acceleration of the streams, namely, the height of the body of water, and the fall; but then the fall cannot but be different in various parts of the same section; and as the parts next to the bottom will be accelerated by the slope of the bottom, so the parts nearest the surface will be accelerated by the slope of the surface. Above all the dams, retentions, and traverses of rivers, where the bottom ascends, the slope of the surface, as we have said towards the end of the third chapter, contributes greatly to the acceleration of the stream; because, the sections becoming lower on the summits of the dams, from the acceleration which arises from the free fall, the surface becomes more inclined in the part above the dam; and hence the waters are accelerated, and even to a greater distance than they would otherwise be, as they are united by a sort of viscosity and adhesion with the lower waters. The same reason, as will be shown hereafter, principally operates at the mouths of rivers, which extend themselves over the lower surface of the sea, by falling on it from a considerable height above their own bottom: because, as the fall is augmented, the velocity of the waters on the surface of the river is increased, and, by the natural tenacity of the particles, the acceleration is extended

to those other waters that are below. This is the reason why it often happens, that a river from fifteen to twenty feet or more in height is, at its entrance, only five or six feet in depth, without any remarkable expansion of its bed; and that too, although it flows on a bottom which is constantly ascending as it proceeds.

Galileo, in his Discourse on the River Bisenzio, was the first who applied to running waters the theories of inclined planes and of the fall of heavy bodies. On these principles, he has gone so far as to assert, that the rapidity will be the same in two canals of different lengths and windings, provided they are of the same height; that is, if they remain confined between the same extreme limits. However, this theorem is only metaphysically true, when all resistance is abstracted; and facts constantly show, that in sinuous channels, in proportion as the resistances augment, in the same degree the velocities are diminished. Hence Viviani, the disciple and successor of Galileo, in the superintendence of the waters of Tuscany, was right in making those rectifications, in the river Bisenzio, of which Galileo had disapproved. Father Castelli first introduced the element of the velocity arising from pressure into the calculation of the quantities of water that flow in the beds of rivers; and we are obliged to him for several very simple, general, and important theorems: as, for example, that in a river reduced to a state of permanence, without any rise or fall in its surface, the quantity of water which, in equal spaces of time, passes through and is discharged by all its sections, will be equal; and, at the same time, that, on the same suppositions, the medium velocities in the different sections will

be in reciprocal proportion to the amplitude of the sections. But the theory of the velocity arising from the pressure of the upper waters was placed in its proper light solely by Guglielmini and by Grandi. Torricelli, in his writings on Standing Waters, was the first person who noticed the acceleration arising from the slope of the surface.

The velocity arising from the free fall would be subject to the same laws as that of all other heavy bodies in falling; that is, it would be as the square root of the whole height, if the irregularities of the bottom, the windings of the banks, and the several other obstructions which are met with in the course of the stream, did not considerably impair it. All rivers, even before they have been greatly increased by a union with their affluents, have a velocity much less than that which they ought to have, considering the height of their fall. Father Grandi, in the thirtieth Proposition of the second part of his Treatise on the Motion of Waters, has pointed out the method of making deductions for what the above mentioned obstructions may have taken from the primitive rapidity of the stream. He states, that it is necessary, in the first place, to ascertain by experiments the velocity of the surface of the river. This may be done, either by measuring the space through which a floating body passes in a given time; or by means of a wheel whose flapboards strike the surface of the stream, by counting the number of its revolutions in a given time; or by measuring, by means of a quadrant, how far a weight suspended from the centre of the quadrant is turned from the verticle line by the force of the surface of the current, because it is well known that the tangents of the deviations of pendu-

lums ought to be proportional to the stroke and force of the stream, that is, to the velocity and the number of particles which strike it in a given time, or, what is the same thing, to the square of the velocity. This done, it is next to be ascertained by known methods what height will correspond with this velocity, or, in other words, from what height a body must fall to acquire a velocity equal to that with which the surface of the river is moving; and, lastly, this height is to be added to the whole height of the section, to obtain the effective height with which the actual velocity agrees: this is what Father Grandi calls *the equivalent origin of the river.* He thus asserts, that the velocity in the different parts of the water ought to be, not as the square root of the actual height of the section (otherwise the water at the surface could have no motion, as it has no other water above it), nor the square root of the height taken from the real origin of the river, as if the waters met with no resistance in their course; but, as the square root of the effective height, which should be measured by the equivalent origin.

The velocity, which arises from pressure in the horizontal beds of rivers, would also be in proportion to the squares of the real heights of the columns of pressure, if the case of the particles of water which flow in the bed of a river were exactly the same with that of water flowing out of apertures in a vessel of equal height. Wolff, in the twenty-ninth Theorem of his Hydraulics, has thought, that, to prove the identity of the two cases, it was sufficient to say, that, in the one and the other, the water is put in motion by the pressure; and that, accordingly, in the openings of vessels, and in the sections of the hori-

zontal beds of rivers, the particles, which are equally distant from all surface, ought to have an equal velocity. Guglielmini, in the second Proposition of his Third Book on the Measurement of Running Waters, has given another view of the case. He supposes the whole horizontal canal to be cut by a vertical plane, which should obstruct the course of the stream, and in which should be opened successively several holes through which the wafer might begin to flow; and he has asserted, that the water will flow out of each hole with the same rapidity that it would possess in the free and horizontal bed; whence Guglielmini has inferred, that, if the holes were multiplied to such a degree as to form altogether the entire opening of the section, the velocity of each particle of water would be precisely the same as if it had flowed from a vessel of equal height. The conjectures, by which Torricelli endeavoured to prove that the velocity with which water flows out of apertures in vessels is as the square root of the heights, should be equally applicable to the case of horizontal beds; because, by plunging an open tube into a river, to any depth whatever, the water will rise in it to the level of the surface of the river. Now, since it rises solely from the pressure of the waters that are higher than the opening into the tube; and, moreover, since the pressure is always the same, whether the tube is immersed in the water, or is taken out of it; the velocity with which the water enters into the opening, and with which it flows in the horizontal bed, ought to be the same as that with which it can rise through the whole height of the section, and, consequently, as the square root of that same height.

Although these conjectures and other similar rea-

sonings do not rise to the strict rigour of mathematical demonstration, they suffice, nevertheless, to show the very high probability or the physical certainty of that which we have undertaken to prove. It would seem that the very analogy of nature would lead us to adopt the law of the case of water flowing out of vessels as that which regulates the case of water flowing freely in the beds of rivers. The second case is even strengthened by experiments and observations. Zendrini, Part II. chapter v. of his "Treatise on the Laws and Phenomena of Waters," having examined with the pendulum the velocities at different places and in various sections of the Po, found that they were nearly proportional to the square roots of the heights when the velocities were not very great. Nor did he ever discover any sensible difference, except in the case of very great velocities, when, the plummet being forced upwards, the string was so sensibly bent that it was not possible to measure correctly the motion and the impetuosity of the stream by the deviation of the pendulum. The truth of this law has always been confirmed by all the experiments which have been made with the hydrometrical flask, invented and proposed by the Bolognese in 1721, in which the quantities of water which entered in a given time by a small aperture left open at the top, and which were collected in the flask, sunk successively to different depths in stagnant as well as in running waters, were at all times nearly in proportion to the square roots of the heights. Father Grandi, in relating these experiments in the forty-sixth Proposition of his First Book, appears not to lay much stress on them, because, when the hole was held level with the water, not a single drop entered the flask,

as if the surface of the water had been so carried along by the under-current that the water below the surface, being opposed by the sides of the flask, caused that of the surface to turn to the right and left, without being able to enter at the opening. This phenomenon, however, was precisely that which was to be expected, on account of the tenacity and adhesion of the particles of water, of which we have already spoken, and of which we shall treat more fully in the fourth chapter of the Third Book.

On a review of the whole, it must appear to be sufficiently ascertained that the velocities of water, though they arise from different causes, either from the free fall or from the pressure of the higher waters, have only one law, and are proportional to the square roots of the heights, either actual or effective,—that is, they are in proportion to the square roots of the actual and absolute heights of the sections when the surface of the water has no perceptible motion; and when the motion of the surface is perceptible, they are proportional to the square roots of the actual heights augmented by the height due to the velocity of the surface. This theorem supplies an easy method for calculating the quantity of water that flows in any river. The elements of the calculation are the following:—

A heavy body, in falling freely, passes in one second of time through $158\frac{13}{14}$ inches of the foot of Bologna; and, with the velocity acquired at the end of its fall, it would in an equal time pass through $317\frac{6}{7}$ inches. This granted, if there be taken a parabola in which the abscissa is $158\frac{13}{14}$ and the corresponding semiordinate $317\frac{6}{7}$, all the other semiordinates will express velocities corresponding with

the heights of their respective abscissas; and by dividing the square of the semiordinate by its abscissa, the parameter of the parabola will be obtained, which will be $635\frac{5}{7}$.

The space run through in one second by a body floating on the surface of the river, divided by the same parameter, will give *the height due to the velocity of the surface;* which, added to the actual height of the river, will give the whole *effective* or *equivalent height.*

The square root of the product of the equivalent height by the parameter will give *the velocity at the bottom of the section.*

Two-thirds of the product of the velocity at the bottom by the whole equivalent height, *minus* two-thirds of the product of the velocity at the surface by the height added to the actual height, will give *the mean velocity.*

Finally, the product of the mean velocity by the actual breadth and the actual height will give *the quantity of water that passes in one second through the rectangular section.* In *trapezium sections* it is necessary to calculate the quantity of water which passes through all the perpendiculars of the triangles formed about the greatest inscribed rectangle, but the method of calculation is always the same.

I have applied the preceding rules to different cases, but principally to that of the waters of the Bolognese. Thus, supposing the velocity of the surface in the torrent Lavino, before its opening into the Samoggia, to be three miles per hour, or equal to 180,000 inches,* and taking the reduced breadths and

* The Bolognese mile, which is to the English as 23 to 20, contains 60,000 Bolognese inches.

the extreme heights in the greatest floods at two different sections which approached the nearest to a rectangle, and which, in the records of the last visit, are distinguished by the letters Q and P, I found the quantity of water which passed in one second through the first section to be 8,219,112 cubic inches; and that which passed in the same space of time through the second section to be 11,844,043 cubical inches. In the same manner, supposing that in the Samoggia alone, before the confluence of the Lavino, the velocity of its superficies was equal to three miles per hour; and taking the measurements given of the two sections marked by the letters O and N, I found that the quantity which passed by the first was 21,085,741 cubical inches, and by the second 38,012,504. The results of the calculations being so different in the two different sections, it becomes necessary to observe that the first section of the Lavino, as well as the first of the Samoggia, was taken on a much more rapid and sloping bottom than that on which the two lower sections were taken. The greater inclination of the bottom, by increasing the acceleration of the waters, necessarily rendered the actual heights less, and the velocities of the surface always greater, in the two first sections than in the two second. If we had more exact observations concerning these very velocities, the calculations might be made with greater accuracy. To arrive as near the truth as can be expected in calculations of this sort, we will take the arithmetical mean, as is commonly done, to combine the differences of similar results, and give 10,031,577 for the flow of the Lavino, and 29,549,122 for that of the Samoggia, making together 39,580,699 cubic inches, which comes very near to the calculations for

the two other sections taken in the Samoggia, below the opening of the Lavino; since, in again supposing the velocity of the surface of the stream to be three miles an hour, the flow of the first section would be 37,641,360, and that of the second 42,468,495, and the arithmetical mean, 40,054,927 cubic inches. We consider ourselves, therefore, as pretty near the truth when we suppose that the quantity of water in the Samoggia, united with the Lavino, and that in the Samoggia alone, are to each other as 4 is to 3. Although the elements of this calculation may not be perfectly correct, and though there may be a considerable difference in the absolute quantity of water, nevertheless, as the calculations have been made in the same manner in all the sections of the two torrents when united as well as when separate, and the arithmetical mean has been taken between the two different results, it is impossible that there should be any very great error in the determination of the proportion or ratio of the flow of the waters; and this is sufficient for what we shall have to say hereafter.

The calculations for the Reno may be made with less uncertainty, as the bottom of its bed is more regular. Former observations assign to the velocity of its surface about three miles and a half per hour; and as they were made with very light floating bodies, they should be preferred to other more recent experiments, because these were made by means of some fascines thrown into the river, which, being considerably under water, participated not only in the velocity of the surface, but also in that of the lower strata. On these suppositions, I calculated two sections of the Reno, which appeared to me sufficiently regular to leave no room to apprehend that, in calculating

their flow by their reduced breadths, and by the heights of their greatest floods, one might not come very near to the proportional quantities of the waters carried. I found that the first section transmitted 111,749,323 cubic inches in one second, and the second 87,950,554; of which, taking the arithmetical mean, I ascertained that the flow of the Reno was 99,849,938 cubic inches; and hence, that the quantity of water in the Reno alone was, to the quantity of water in its stream when united with that of the Samoggia, very nearly as 5 to 7. Taking the measurement of the other torrents of the Bolognese in the most regular sections, as they are exhibited in the table at the end of this Book, I find that, supposing the Reno alone to contain 100 parts, and the Samoggia, united with the Lavino, 40, and consequently the Reno after its junction with the Samoggia, 140; the Navigable Canal would add 2; the Savena, in floods, 20; the Idice, 24; and the three other inferior torrents—the Centonara, the Quaderna, and the Sillaro, taken together, 25. Those who have calculated from other measurements the streams of these torrents, and who, in considering their sections as trapeziums, have been more particular in taking account of their little irregularities, have obtained results which differ but little from the above. But as it is sufficient for my purpose to approximate, as near as it can be done, on all such subjects, to the proportions of the quantities of water, I do not consider it requisite to push the calculations farther.

CHAPTER III

ON THE VELOCITIES OF THE WATERS IN ARTIFICIAL CANALS.

We have seen by what law water is accelerated in single rivers, both from the pressure of the waters and from their fall. In rivers that unite with others, there appears to be another element of which it is necessary to take account; that is, the shock and the composition of velocity and motion which take place at their junction. Guglielmini, in the fourth Proposition of the eighth chapter of his great work on the Nature of Rivers, began the application, to running streams, of the principle of the composition of motion. In the Memoirs of the Academy of Sciences at Paris for the year 1738, M. Pitot has used the same principle to determine the mean direction which the waters of two rivers will take when freely united together; but to find the common velocity of the waters after their confluence, he supposes, that, in running waters, as in the collision of hard bodies, the same quantity of motion is invariably preserved; and from this hypothesis he draws as its consequence, that the common velocity of the united rivers is equal to the quantities of motion in the two separate rivers, divided by the sum of their quantities of water. Fontenelle has observed in his history of the same year, that this does not agree with the phenomena of

waters united in the same bed, and by their union acquiring a greater rapidity. Father Grandi, in the fourth and the fifth chapters of his First Book, has endeavoured to decide by the same principles of the composition and resolution of motion, not only the direction, but also the absolute velocity of waters, which either unite or divide. For this purpose, he has invented a floating body, which may be attacked at the same time in the confluence of the stream of two rivers, by the forces of the receiving and tributary currents in their first directions; whence it ought to happen, according to the laws of mechanics, that the floating body will continue its movement in an intermediate direction. Taking it for granted, moreover, in the forty-sixth Proposition, that the motion of the floating body is common to it with the course of water in the river, after the junction of the united streams, he concludes that this course should naturally have an intermediate direction between those of the recipient and the tributary waters. This laid down, he, in the twelve corollaries and two scholiums that follow, applies generally to running waters all the theories in mechanics on the composition of velocities; and in the third scholium he maintains that if the banks of the receiving stream do not yield a little below the opening to the impression of its tributary, the thread of water in the receiver must preserve the same direction which it had before, increasing, however, its former velocity by a part in proportion to the velocity of the tributary stream, as the cosine of the inclination of the rivers is to radius. Whence it will follow, that if the thread of water in the tributary should second by its direction that of the thread of water in the recipient, in making with it, as is gene-

rally the case, a very acute angle, the velocity in the common bed would be equal to the sum of the velocities of the recipient and affluent streams; since the velocity which the floating body would have in the thread of the united rivers would be precisely the sum of the two separate velocities.

If this principle were admitted, it would follow that the sections of the receiving stream could not be considerably augmented by the junction of the tributary, for the very reason that the quantity of water augmenting the velocities would be compounded of this augmentation, and that the flow of the current would become more rapid than before. But, besides the general difficulties which we have before urged on the whole subject of hydraulics, several other particular doubts might be started in regard to the hypotheses of Father Grandi. One might, especially, deny, that the case of a single body floating is the same as that of two currents of water passing from two separate beds into one. But setting apart these hypothetical theories, we may still follow the method we have already commenced, which is, to discover the laws of Nature by observing her phenomena. On this subject, however, very little information is to be obtained from former authors. Guglielmini, at the end of his seventh chapter, in considering the celebrated phenomenon of the Po of Venice, which receives the branch of Ferrara and the Panaro, without any enlargement of its bed, has stated in general, that a small river may enter into a large one without increasing either its breadth or its height; and he is of opinion that this might happen without any lateral dispersion, because the whole of the increased body of water continued in motion by following the direction of the

thread of the stream. On the hypothesis that all the sections were effective, and that the velocities before and after the confluence of the two rivers were as the square roots of the actual heights, the cubes of the heights would be as the squares of the quantities of water which are discharged in an equal time by the sections. Manfredi, in the third chapter of his Reply to Messrs Ceva and Moscatelli, has deduced from this theorem, that the Reno, adding in floods $\frac{1}{31}$ part of water to the Po, supposed to be also equally flooded, could not raise its height more than eight inches and one half, or nearly $\frac{1}{61}$ part. But reflecting afterwards on several other circumstances, and principally on an experiment several times repeated, viz., that the waters in the drain of Burana, whether added to or deducted from those of the Panaro, occasioned no sensible difference in the height of that river, Manfredi maintained in the fourth chapter, that, in fact, the elevation of the Po must be very small for any augmentation which the waters of the Reno could give to its stream.

The controversies that have lately arisen on the subject at Bologna and in Holland have caused this important part of hydrometry to be amply discussed. The Great Rhine divides itself near Emmerik into two branches nearly equal to each other, the Wahal and the Rhine. The bed of each of these branches is nearly as large as that of the whole river before its division; and when the waters rise, they are at an equal height in the one and in the other. The second branch divides itself again towards Arnheim to form the Issel, and the section of the Issel is not very different from that of the Rhine. The first division of all the waters of the Rhine was begun under the

Roman generals Drusus and Corbulo; it was afterwards continued in later ages by a great number of subdivisions. This great multiplicity of channels, though productive of very great advantages to the navigation and commerce of Holland, draws after it very fatal consequences. The waters, divided into so many branches, lose the rapidity and strength which are required to sustain and push forward those heterogeneous substances which they transport. The constant rising of the bottom renders the draining of the waters from the fields more difficult, increases the expense of the necessary embankments, and always augments the damages which these extensive low lands suffer when the dikes break and threaten the whole country with utter ruin. To secure that part of Holland which lies between Rotterdam, Utrecht, Amsterdam, and the ocean, it was proposed in 1754 to form in the Leck, which is another branch of the Rhine, a cut with sixteen sluices, by which a part should be discharged into the Meruva, which is the junction of the Meuse with the Wahal. M. Genneté, already known by several small works on agriculture, the Purification of the Air in Hospitals, and the Mode of preventing Chimneys from Smoking, published on this occasion his "Experiments on the Course of Rivers." This work is in the form of letters addressed to a Dutch magistrate.

Genneté has asserted that the proposed alteration would avail nothing towards the diminution of the height of the floods; and proposes, in lieu of it, to reunite all the waters of the Great Rhine in the ancient branch of the Issel, and in this manner to conduct them by the shortest road to the sea. He maintains that, by the union of all the waters, their rapidity

would be increased, whilst the amplitude of the sections would continue the same; and that in consequence the waters would have more strength to deepen their bed, and to prevent those deposits that are successively made in it. He supports his opinion by the directly contrary effect produced from the actual divisions of the Rhine; and he adds, that this river, before it is divided in Holland, receives at Mentz the Mayne, whose flow of water is nearly as great without its being possible to observe any perceptible difference in the dimensions of its bed. In like manner, between Mentz and Cologne it receives the Moselle and several smaller rivers, and yet the bed of the Rhine is narrower at Cologne than above its confluence with the Moselle. But as he possessed no correct measurements of the sections of the Great Rhine above and below its affluents, he sought, by the aid of experiments, to find the difference of the velocities and heights in some little canals in which the difference of the quantity of water was already known. For this purpose he caused to be constructed at Leyden an artificial river, which was supplied with water by means of a vessel five or six feet high, and into which he discharged other small streams by means of sluices. He gave to the bottom of the recipient and of all the tributaries an uniform declivity of one foot in twelve hundred, and he observed all the variations that occurred either in adding the tributaries or in retrenching their streams. These canals were at least six or seven inches in breadth, as I have been informed by M. Alamann, a celebrated professor in the University of Leyden, who was present at the course of experiments made in 1755. During the time of my abode at the Hague, I conversed on the

subject with some of the commissioners, who had been present by order of government, and with several other persons, who also certified their truth. The result of these experiments was as follows:—

Genneté, having first noted the height of the water in his only recipient, let in a stream, which added one-half to that water, and afterwards another, which added another half. He observed that while the quantities of water in the recipient were successively as 1, $1\frac{1}{2}$, 2, the height of the water was to sense the same; and that thus the velocities and the quantities of the fluid increased in the same proportion. Having then measured the actual velocities by means of a small machine which he had placed on the river at the time of the experiments, he found they were really in the proportion of 1, $1\frac{1}{2}$, 2. Finally, to find the limits beyond which the increase of height began to be sensible, he caused other streams, equal to the first, to flow successively into the new river. The first degree of increase that appeared was when the augmentation of the quantity of water in the recipient was three times greater than what it was in the beginning; and this increase was $\frac{1}{48}$ part of the whole height. The second was $\frac{1}{24}$, which was observed when the quantity of water was quadrupled; and afterwards, when the quantities of water were as 5, 6, 7, the increase of height was $\frac{1}{16}$, $\frac{1}{12}$, $\frac{1}{8}$. From the union of the streams passing to the division, Gennetė gave his artificial river its greatest possible height, by the introduction of so much water that it was ready to overflow its banks; then, raising a sluice, he let out about $\frac{1}{16}$, and observed that the surface of the water was lowered at first, but that the derivatory canal was scarcely filled when the surface returned

to the same height as before, the waters of the canal and of the river afterwards maintaining the same level. Another opening was made, which took off the half of the water in the entire river, but did not produce a greater effect than the former. It is true that when these canals were open, and things were reduced to a state of permanency, the velocity, measured by the little machine of which we have spoken above, was found to be diminished. The limits of the diminutions were the following:—When two equal streams were introduced together and at a distance from their mouths, two cuts, each of a section equal to that of the whole river, were opened, the waters fell $\frac{1}{16}$. When the equal and united streams were five in number, and the section of the two canals of derivation was as before equal to that of the whole stream, the abasement was $\frac{1}{24}$. It was the same when there were three canals of derivation and six accessory streams. With two canals of derivation and six streams all equal, the abasement was $\frac{1}{48}$.

M. Gennete's book was published exactly at the period when I was engaged in the Bolognese controversy; and on comparing together the observations made on the rivers, it appeared to me, that it might be inferred from them that frequently there is not any sensible increase of height, even when there is a considerable augmentation in the quantity of water; and, therefore, that the velocity of the water increases sensibly in the same ratio as its quantity. Although the experiments made on little canals can never serve as a rule for the regulation of great rivers, they are sufficient to show, that Nature, on the small scale and on the great, acts always by the same laws, and is very analogous to herself. It was on account of

this analogy, that I inserted in my book the result of the experiments, and that I immediately made them known in Italy. There was no person, out of the whole number of those who examined them, who denied that there might exist a case in which these experiments might be verified, as appears by the various reports inserted in the Florentine Collection, and chiefly after page 544 of the sixth volume. Some persons have deemed them utterly untrue; and others have thought that they led to the most absurd consequences, since, by applying to rivers the observations Genneté had made on artificial canals, and taking in the most extended sense the limited results of his experiments, they conceived that the natural conclusion would be, that one might increase, without any limits, even *ad infinitum*, a body of water, without visibly increasing its height. Such an absurdity has no connection with the observations made on a small scale by M. Genneté, nor with the particular position which I had established by observations made on a larger scale in our rivers. My position was precisely this, that as the Reno receives the Samoggia without any perceptible difference in the amplitude of its sections, so it might also receive the Savena, the Idice, and the other inferior little torrents, without any sensible augmentation, either in depth, or in breadth.

The experiments have been carefully repeated, at Ferrara, in 1762; again repeated, at Rome, in 1763; and again begun anew at Ferrara, in 1766, with results entirely different. On the supposition that Genneté has fairly and exactly stated his own experiments, which I have had attested by several eye-witnesses, and on the further supposition, in which all the world were agreed, that Genneté's experiments might be

found correct in some particular cases, it only remains to be said, that the cases at Rome and at Ferrara were not the same with that at Leyden. M. Genneté has offered to come and recommence himself his experiments in Italy; but neither in his book, nor in his private letters, has he detailed the circumstances of his artificial river ; as, for example, what were the precise breadth and height of the sections, how the quantities of water were adjusted, at what distance the tributaries entered, and the ramifications were formed. Genneté has, however, clearly proved in his letters, that the Roman experiments presented nothing that could agree with the rules of hydrometry. It is certain, that the plan of the machine described in the fifth plate of the sixth volume of the Collection of Florence, is sufficient to show that the breadth of the separate canals was not uniform ; that, at the point of their junction, the streams met in a different manner ; and that the whole construction was very different from that of Genneté. Moreover, the Roman machine was too small, the smaller canals being only 1 inch in breadth and 12 feet in length as appears by page 512 of the Collection above quoted. It is very easy to see, that the resistance of the bottom and sides, in such small streams, could not but disturb the whole results of the experiments. The same may be said of the machine used at Ferrara in 1766, of which the canal was 10 feet 5½ inches long, 2 inches wide, and 2¼ deep, as appears from page 533 of the same Collection. Further, the waters entered it by holes opened in the reservoir itself; so that there was nothing that could bear a resemblance to a river attacked and taken in flank by a tributary stream.

The machine used at Ferrara in 1762 had a nearer

resemblance to that of Genneté's. The recipient was 199 feet long and 7 inches wide; the tributaries were of the same width, and were placed so as to enter laterally at an acute angle. The result of the experiments was, that, in permitting the first tributary stream, containing nearly an equal quantity of water, to enter the recipient, the augmentation of the height was nearly one half; and this augmentation became almost another half on the admission of a second tributary. If there were any wish to apply these experiments to hydrometry, all that could be stated against it would be, that the quantity of water was too small, and the velocity of the surface too great, to bear any resemblance to a river; the rapidity at the surface being, in the Ferrara experiments, 199 feet in four minutes, or 2985 feet per hour, was about a fifth of the velocity which we have already assigned to the surface of the Reno; whilst the body of water was only 4100 cubic inches per minute, that is 146 thousand times less than the whole flow of the Reno in floods. But it is not natural, that, when all the other elements of a river are thus reduced, the element of the velocity at its surface should, alone, not also decrease in some kind of proportion. Besides, I am unwilling to have it even pretended, that the laws of great rivers are to be established upon what takes place in such streamlets of water. I will, therefore, not enter upon the other experiments, which were tried at Rome and Bologna, and which agreed better with those of Genneté. I leave to experimental physics all these subtilties of art, and proceed in my endeavours to trace out in Nature the principles and rules of hydrometry.

CHAPTER IV.

ON THE VELOCITIES OF RIVERS, UNITED AND DIVIDED.

In the last inspection of the waters of the Bolognese, by so many able reporters and mathematicians, there were taken, with the greatest care and the utmost precision, four sections of the Reno above the entrance of the Samoggia, and five other sections below that entrance. The greatest heights were determined from that flood of the Reno which came down on the 15th of November 1761 ; and these very heights, the breadths reduced, and the sections, were found to b as follows :—

		Greatest Heights.	Breadths Reduced.	Sections.
		Feet.	Feet.	Square Feet.
Above . . .	the entrance.			
	No. I. . . .	17½	176	3080
	II. . . .	17	157	2669
	III. . . .	16½	151	2491
	IV. . . .	16½	207	3415
Below . . .	the entrance.			
	No. I. . . .	14½	158½	2298
	II. . . .	13⅓	166	2213
	III. . . .	13	198	2574
	IV. . . .	13½	153	2065
	V. . . .	9⅓	259½	2422

The four first inferior sections were taken in places far distant from the valleys; and all the sections, at places where the upper superficies of the river is parallel to its lower superficies, and where the lower

superficies is parallel with the bottom: whither, of course, the acceleration arising from the free opening of the fractures into the valleys could not extend. The lowest of the four sections taken in the upper district is two miles distant from the mouth of the Samoggia; and, consequently, there could be no suspicion of any reflux. Almost all the upper and lower sections have been taken where the bed is very regular, and where there are no angles or turnings, and where it is, consequently, impossible to say, that the diminution of the windings contributed to the acceleration of the stream. The fresh that came down the Reno, on the day above mentioned, did not in fact reach its utmost height at the same time as that of the Samoggia; because it seldom happens that the floods, in rivers whose courses are different, occur exactly at the same time. However, as the difference of their course is not very great; since the origin of the Reno is not far distant from that of the Samoggia, and both these rivers swell from the same causes, rains and melted snow; it always happens, that, whenever the Reno has reached its utmost height, the Samoggia is greatly swelled. In reality, the greatest height of the flood of the Samoggia, on the day in question, preceded that of the Reno but by a few hours. The Reno, then, did receive a considerable body of water from the accession of the Samoggia, without increasing, either in height or in section.

The same effect is produced by the confluence of the Lavino with the Samoggia. Two sections of this river were taken above its mouth; the one, at the distance of 1132 perches,* on a very regular bottom,

* The Bolognese *perch* contains 10 Bolognese, and about 12¼ English feet.

and for this reason incapable of being compared with the sections taken below it, in places where the slope is much less; the other, at the distance of 356 perches, on a very regular bottom. The greatest height of the second was 18 feet, on a reduced breadth of 58 feet; and the whole section was 1044 square feet. The Samoggia, immediately below the entrance of the Lavino, falls from a very rapid elevation of nearly four feet, as appears by the profiles; so that the acceleration of the fall must prevent the reflux of the united streams whatever it may be from extending much above the entrance; and further, the declivity of the Samoggia, in these 356 perches, is more than a foot; from whence it follows, that, when the reflux at the confluence of the Lavino would keep up a foot of dead water, or perform the functions of a wear a foot in height, the horizontal line drawn from the top of this wear could never possibly reach so distant a bottom, and thus the measured section would be free. Finally, above and below this section, the surface is parallel to the bottom: nor is there any appearance of regurgitation. Below the entrance of the Lavino, where the bottom of the Samoggia is more regular, and proceeds parallel to the surface, the utmost height is $15\frac{2}{3}$ feet, on a reduced breadth of $70\frac{1}{2}$ feet; and the whole section is 1107 square feet. The Samoggia and the Lavino running near each other, and having almost the same course, their floods always come down at the same time. Thus, although the quantity of water is increased nearly one third in the Samoggia after the junction of the Lavino, as has already been said, and although the slope of the bottom is considerably diminished in the Samoggia, nevertheless the height is less, and the whole section very little larger, than before.

The operations carried on in the Gaiana were not less exact; yet, although it increases by nearly a half the body of water in the Quaderna, it sensibly augments neither its height, nor the magnitude of its sections. The section of the Tiber, above the entrance of the Teverone, is 4013 square palms;* and below the confluence, 4071. We have, besides, several other examples of running streams considerably augmented, without any visible increase of their height or breadth. Thus we find in the Process-verbal of the Observations made on the Po in the visit of 1719 and 1720, that, the Po having been observed at the time of one of its greatest floods, which happened in 1714, none of the inhabitants of Lagoscuro, or of the other places in the vicinity of the Po, were able to discover any sensible difference in its height, although there was, at the same time, a great fresh in the Panaro. We also read, in the same Notification, that during the floods in 1719, neither the Panaro, nor the Secchia, considerably raised the surface of the Po, although the utmost height of its flood certainly occurred at the same time with that of the Secchia. We read, in the Collection of Observations for 1728, that, having made the experiment of placing marks in the Panaro, and of letting in and afterwards withdrawing the waters of the great drain of Burana, they observed in the Panaro no sensible rise in the first instance, nor any visible decrease in the second. These three facts have been particularly attested by Eustace Manfredi, whose testimony is worth that of all the others.

No objection can be made to these facts; for it

* The *architectural* Roman *palm* is equal to ·732 of the English foot; and the *square palm*, therefore, to ·536 nearly of the English square foot.

cannot be said, that the quantity of water in the affluent bore no sensible proportion to that of the recipient stream, nor that the sections of the recipient were not effective; neither can the invariability of these very sections be attributed to any other causes than an increase of velocity in the united waters, proportioned to the increased quantity of water itself.

What has been observed in the conjunction of rivers, is also seen in their derivation or division, where it often happens, that in diverting from the principal channel a considerable body of water, that which is left behind is not visibly diminished, either in height or in breadth. Although Genneté has not furnished us with correct measurements in reference to the observations which he has reported, they are, nevertheless, confirmed by another observation made on the Po of Venice, and fully detailed in the celebrated Avis of M. Riviera. The section of the branch d'Ariano, separated from that delle Fornaci, is 2365 square feet; that of the principal trunk, before the separation, is 12,070; and that of the other branch delle Fornaci is 12,330½; and lastly, the reduced breadth of the principal trunk is 35 feet less than the breadth of the branch delle Fornaci, and the height is only one inch and a half greater in the former than it is in the latter. With so small a diminution of height, and an increased breadth of 35 feet, they were enabled to draw, from a section of 12,070 square feet, a sufficient quantity of water to form a section of 2365 square feet, by the sole combination of the difference in the result of the velocities in the two canals. As all the water that passes through the two inferior branches delle Fornaci and d'Ariano, is the same as had previously passed by the main trunk of

the Po, before the division, there can be no reason to doubt but that the same thing must happen, if, by a retrograde movement, their branches should be united again into a single bed; and this so much the more readily, as the confluence will take place with a more acute angle than that at the place of separation. This observation is sufficient to show the inutility of all derivations, even where they would draw off, from the main trunk, a quantity of water bearing a sensible proportion to the whole remainder of the river.

It is an hydrostatical paradox, commonly taught by Italian authors, and uniformly confirmed by experience, that you do not diminish the *height* of the waters in great floods by lessening the *quantity* of the water. Father Castelli, in the thirteenth Corollary of his first book on Running Waters, has disapproved of the division formerly made of the Po at Buondeno, and which was afterwards abandoned in the year 1638. Guglielmini, in his twelfth chapter, has confirmed the opinion of Castelli, as far as regards the little utility to be derived from discharging-sluices, as well from the small quantity of water which they let off in proportion to that of the whole river, as from the very small retrenchment that they make from the height to which the river would have risen, if they had not been made.

Eustace Manfredi, in a paper never printed, has clearly proved the inutility and the danger of all the cuts which some persons had proposed to make in the right bank of the Secchio. Experience has in like manner demonstrated the inutility of the cut made in the embankment on the right of the Arno, at le Fornacette, by means of which it was formerly expected that the city of Pisa might be secured against

inundations. This cut having been made in 1740, three or four breaches occurred in the upper bed of the Arno, and yet at Pisa there was no perceptible diminution in the height of the floods. The cut was made anew in 1761, during the month of November, at the time of a very great flood, yet the waters continued to rise so high that some persons could not be persuaded the cut had been made. The fresh came down in a few hours on the night of the 14th, and continued with slight variations till the evening of the 15th. At seven o'clock, that same evening, they made in the left bank of the river at le Fornacette an opening of 8 braces, which was soon widened by the waters to between 28 and 30. However, notwithstanding the amplitude of the section and the quantity of water that issued by it, the river continued to rise at Pisa; and, about eleven o'clock, it reached the greatest height that it had ever attained in the memory of man. The next morning, I observed all the arches of the bridge, in the marshes, covered by the waters; there was in the centre bridge only a single arch, and two in the sea bridge, that were not entirely covered. In the afternoon of the 16th, the flood increased afresh; and it was not till towards the evening that it began to subside.

I might add to my own observations those made in other rivers with which we are acquainted. The canal made by order of the Emperor Nerva, to draw off the superfluous waters of the Tiber, at the time of its greater freshes, did not contribute in the smallest degree to prevent the inundations, as Pliny has assured us in his letters. The two sections of the Tiber given in the plan of 1744, above and below the separation of the Canal of Fiumicino, have very nearly the same

breadth. The reduced depth in the upper section is ten palms,* and the whole section is nearly rectangular: the reduced depth in the lower section is nine palms;† but, as the actual depth on one side of the section reaches as far as eighteen palms,‡ in reducing it to a regular and rectangular section, the waterway will be found nearly the same. Thus the branch of Fiumicino produces no sensible advantage to that of Ostia. The two relieving sluices that Vincent Viviani caused to be made in the Celone, which is a tributary of the Chiana, have caused the filling up, and the loss, of the principal trunk. One may consult, on this subject, the opinion given by Thomas Perelli, a learned mathematician, on the derivations from the torrent Maroggia. One may also inspect the discourse of the celebrated Lorgna on the inundations of the Adige, which sufficiently proves, that all derivations made in that river have only produced a heightening of its bed, and thereby rendered the floods more dangerous.

To sum up the whole, it is very certain, that the height of united rivers increases in a much less proportion than the body of water by which they are augmented; and that frequently, with a considerable addition to the body of water, no sensible augmentation of height is obtained; whence it results, that, when this is the case, the velocity of the water increases perceptibly in proportion to its quantity. This phenomenon forces itself on the notice of every one who compares the height and the section of a river with the sum of all the heights and of all the sections of its tributary streams. All the observations which have yet been made on rivers, large and small, con-

* 7·32 English feet. † 6·588 English feet.
‡ 13·176 English feet.

firm the same fact. The great Rhine, after it has received the Mayne, which is nearly as large as itself, does not appear visibly augmented; and afterwards, when it is divided into two or three branches, its surface is not apparently lowered. The Danube receives the Inn, almost equal to it in dimensions, without becoming either broader or deeper. The greatest freshes in the Secchia and the Panaro occasion no rise that is observable in the height of the Po. For similar reasons, the divisions of the Po, and of the Tiber, do not cause the lower sections to be much less than those of the principal bed. The Tiber at the entrance of the Teverone, the Panaro at the drain of Burana, the Quaderna at the junction of the Gaiana, do not experience any sensible difference in their sections by the increase of the body of water. So also the Samoggia, after being augmented one-third by its union with the Lavino, and the Reno increased by a little less than two-fifths in consequence of its junction with the Samoggia, do not visibly augment either their breadth, or their height, in great floods. No hydrometrical truth can be confirmed by a greater number of uniform observations. Wherefore, in general, the velocities of united rivers increase nearly in proportion to their quantities: and hence, in the particular case of the Reno, should its stream be augmented two-sevenths by its union with the Savena and the Idice, instead of increasing its section, it would accelerate its course in proportion to the increased quantity of water received. This particular conclusion will suffice for what we shall have to say in the sequel.

CHAPTER V.

ON THE SLOPES OR DECLIVITIES OF RIVERS.

All rivers which carry sands and slime, though they flow in their own beds without any increase from the union of new streams, dispose their bottoms, in the lower parts of their course, on a less slope than they had in the upper; that is, the declivity diminishes in proportion to the distance they have run from their sources, as has been taught by Guglielmini in the seventh rule of his fourth chapter. All the levels that have been taken in rivers of this nature, between one tributary and another, allowance being made for some irregularities, give a declivity of bottom, which when reduced, gradually diminishes as you descend the stream. Thus, for example, the Reno, in the first 781 perches below the entrance of the Samoggia, has, according to the last levels, a declivity of 17 inches 8 lines per mile; and in the whole space of seven miles and a half, from the Samoggia to the breach called Panfilia, it has a reduced declivity of 18 inches 4 lines, which diminishes to $14\frac{3}{4}$ inches in the three last miles above the breach; and in the time when this river ran to Vigarano, six or seven miles below the existing breach, its slope in the last trunk was only $12\frac{3}{4}$ inches per mile: as may be seen in the records of the visits made by M. Riviera.

The cause of this is, that, in the continuation of

the course, the sands mixing together in various ways, and constantly rubbing and striking against each other, become finer as they go on, and therefore require less force to push them forward: and, although it be true, that the slope of the bottom contributes to the acceleration of the waters, and to the augmentation of their force, nevertheless, if the body of water is supposed the same, it is certain, that, when the substances are lighter, less declivity is necessary to keep the bottom of the bed always well cleared. The same diminution of slope is observed in rivers and torrents, which roll stones and gravels, not because the stones and gravel diminish sensibly in size by the continual friction, but because the largest gravels, and those stones that are the heaviest and the least regular, are gradually left behind. To these different reasons is owing the constant verification of the general principle, that, supposing the body of water to be the same, the slope of the bottom diminishes in proportion as the substances brought down by the currents become smaller and lighter.

If the question is, next, concerning those rivers which are enlarged by their union with others that are less, it is equally certain, that their bottoms will require a fall so much less, as the united body of waters shall be more considerable. This principle has been treated of, at full length, by Guglielmini in in his fifth chapter, and by Eustace Manfredi in his replies to Corradi and Ceva: and it is a principle confirmed by facts and phenomena; for if you measure the slopes of all the streamlets that form a brook, and of all the brooks that form a torrent, and of all the torrents that fall into a great river, the smaller currents will always be found to have a more rapid descent, and a

greater declivity of bottom, than the larger. Barattieri, in the first part of his Architecture, has already observed, that the Great Po, from Cremona to the entrance of the Oglio, flows on a greater slope than that which it has in lower parts. The declivity of the Po, from Stellata, to Lagoscuro, is at the rate of seven inches to a mile; and from Stellata, in ascending to the Mincio, its reduced slope is $8\frac{1}{2}$ inches, as Manfredi has reckoned it in his Dialogues. The slope of the Panaro, above the same place, Stellata, is 18 inches $10\frac{3}{4}$ lines; the slope of the Lavino, alone, is at the rate of $76\frac{1}{2}$ inches; and that of the Samoggia, in the two last miles above the entrance of the Lavino, in the proportion of 23 inches 5 lines to a mile. After the junction of the Lavino, the reduced slope of the Samoggia is no more than $37\frac{1}{3}$ inches, to its opening into the Reno. The slope of the Reno, two miles above the confluence of the Samoggia, is 26 inches 2 lines per mile; and in all the upper space, for 5 or 6 miles, it has a reduced slope of 25 inches : but after the junction of the Samoggia, the slope of the Reno is only about 18 inches, as has been already observed.

In considering these observations in detail, the example of the Po and the Panaro for great rivers, and that of the Reno, of the Samoggia, and of the Lavino, for less rivers, will furnish us with another principle, which is, that if the tributary and the recipient carry to the point of their junction substances nearly similar and homogeneous, the slope of the common bed will be less, not only than that of the tributary, but even than that which the recipient had previously in its own bed. The other levels taken in the Tiber above and below the Teverone, and in the

Quaderna above and below the junction of the Gaiana, confirm the truth of this proposition.

It is certain, that, on the supposition that the sands and the slime both of the tributary rivers and its recipient are nearly alike in quality and in quantity, there will result a river equally turbid both before and after its confluence, and in which the same quantities of water contain the same quantities of earth and sand. But whatever may be the force, which is necessary to keep the floating bodies incorporated, to carry off the deposits, and to preserve the bottom clear, it must depend on the body of water, and on the slope: so if a given body of water in a recipient, while alone, is established on a bottom of a given inclination, this very recipient, after the junction of a tributary, must establish its bed, by means of the increased body ot water, on a less declivity than it had before. All this should equally take place when the waters are highest, when they are lowest, and when they are in their intermediate states. Eustace Manfredi, in the Exposition which he has given of the fourth Corollary to the sixth Proposition of the fifth chapter of Guglielmini, which states, *that the greater the ordinary body of water in a river, the less will be the slope of its bed*, has remarked, that the time, at which the waters are sufficiently strong to push forward any detached substances that may be in the bed, is not limited to the single state of great floods, but that the same effect may be produced, at least to a certain degree, even in the ordinary flow of the stream. It is useless to object, that, when the waters diminish, the quantity of substances brought down by the current do not lessen in the same proportion; and, that as a river then remains equally turbid, it might leave deposits,

if an ample fall in the bed did not supply the place of the diminished height of the stream now reduced. This difficulty, which affects the establishment of the bed of a river whilst it remains single, is wholly inapplicable to those rivers of which the beds are considered as already established, and which afterwards unite; and it will always be correct to say, that if the recipient alone, with a given fall, maintains its bottom quite clear, both when its waters are low, and when they are high or of the common rise, it will, after a union with a tributary, require a less slope to float down at all times its silt, and to sweep away the new deposits.

What has now been stated may be equally well applied to cases where the great freshes do not come down at the same periods, or where, as frequently happens, the tributary has a greater declivity in its own bed than the recipient. In all regulated rivers, on the freshes of a tributary coming down, the stream of the recipient flows back, and depositing sediments above the mouth, may form deposits also below it, if the assistance, which the tributary receives from the low waters of the recipient is insufficient to compensate for the difference of fall which the tributary encounters in passing from its own into the common bed. But the regurgitation can oppose no obstruction to the waters from that point, above the two bottoms, to which the horizontal line drawn from the low surface of the recipient heightened by the flood of the tributary reaches, as has been demonstrated by Father Grandi in the thirty-sixth Proposition of his second book. Thus, the tributary being swelled, and not the recipient, and it being impossible to prevent a reflux of the water, shoals will be formed in the bed,

even in the higher parts; but the first floods that come down the recipient will replace all things in their former state. It is thus that the Samoggia often meets, at the mouth of the Lavino, the deposits which had been left by this river in its last freshes: and it very commonly happens that the Reno meets, in its own bed, the deposits left there by the Samoggia. When, however, the freshes of the Samoggia come down, its bottom is re-established on a fall not only less than that of the Lavino, but even less than that which it had in its own bed. In the same manner, the Reno, in floods, always preserves its bottom on a considerably less slope than that of the Samoggia, as well above as below its entrance. From these examples, one may, on good grounds, conjecture what would happen, if they should introduce into the lower parts of the Reno some other tributaries, which do not convey heavy substances to their mouths, although their freshes do not descend at the same periods; namely, that the slope of the Reno would lessen by degrees at the mouth of the first tributary, in like manner at that of the second, and so on for each of the rest which are farther down.

Corradi wished, by employing some formularies of Parent, to fix the law of diminution in slopes. This geometrician pretended to prove, by some of his reasonings, that the force of friction in a rugged body is nearly one third of the perpendicular force which presses one surface against another; which is conformable to some experiments of Amontons. But, on planes inclined to the horizon, that part of gravity, which solicits the descent, is in proportion to the sines of the inclinations; and the other portion of gravity, which acts perpendicularly to the planes, is propor-

tional to the cosines; and further, in planes whose inclination is very small, the first of these two forces may be neglected in respect of the second: whence the whole force of friction, and the whole force that is required to move a rugged body on an inclined plane, will be proportional to the cosine of the inclination. Corradi has pretended, from this principle, to establish two rules for the gradual decrease of the slopes of rivers whose bottom is not variable: the first, that the cosines of the beds of rivers that are fixed, and which float similar substances, are as the velocities, when these beds descend constantly towards their mouths; the second, that, in two fixed rivers, the one of which the bed descends, and in the other ascends, towards its mouth, the velocity of the first is to the velocity of the second, as the cosine of the first is to the sum of the sine and cosine of the second. But if one wished to apply the first rule to the case of the rivers in the Bolognese, and if, on the supposition of Corradi, one were to reckon that the velocities were as the square roots of the heights of the water, the diminution in the slope of the Reno would be found to be so great for a very small increase of velocity and height, that, at the confluence of the Savena and the Idice, the cosine would be greater than the radius; and the base, or foot of the slope, greater than the bed itself which slopes: by which means the slope would be entirely reversed, and from descending would become ascending, and the streams might flow upwards. This is the principal absurdity to which Manfredi has reduced, in general, the rules of Corradi.

Guglielmini, in his fifth chapter, has considered separately two cases of the establishment of the bottoms of rivers. The first is that which is effected

by the excavation of the water; the second, by alluvions, filling up, or deposition of substances floated down. It is not stated with sufficient clearness, in the Discourse in which this great master on the subject of rivers shows, in the first Proposition of this Chapter, what are the general rules for the slope required in a river, that it may either excavate its own bed, or float all its sediments and leave no deposits. It appears, however, that the whole may be reduced to the following principles, which are in themselves very simple and very clear. If a river, having a permanent bed, flows alone over a given slope; and if, after the junction of some tributary stream, the bottom of the common bed is found to be composed of substances equally removable; its bed may remain equally excavated, even with a less slope than it had before, when the force which the stream employs to tear up the bottom, added to the force with which the matter torn up runs on the inclined planes, forms, before and after the junction, an equal sum. Now, as the relative gravity, which determines the particles of the bottom to descend, is in proportion to the sine of the inclination of the plane, and as this gravity is very little different in two planes whose inclination is nearly equal; whenever the question is of beds whose inclination to the horizon is very small, the relative force of gravity may be neglected, as incapable of preventing the excavations from being nearly equal, both before and after the junction of a tributary when the force and velocity of the stream are the same both above and below the junction. In like manner, since there must be a certain degree of agitation proportioned to the weight, to the mass, to the figure, and to the superficies of the particles of earth and of sand,

to keep them always united and incorporated with the water; it is evident, that, when the waters under consideration are equally turbid, or nearly so, and the portion of earth or sand in an equal quantity of the water is always the same, the sediments may be kept afloat without making deposits, as often as, in the bed of the recipient, the force and the rapidity of the water are the same before and after the junction of the tributary.

Guglielmini has besides left us some more precise rules in the Corollaries to the second Proposition of the Fifth Book. These are the following: *the greater the quantity of water that a river carries, the less will be its fall:* and, *the greater the force of the stream, the less will be the slope of its bed.* But as, towards the end of the second Proposition, he understands, by the force of the stream, the velocity itself, the second rule must be resolved as follows: *the greater the velocity of the stream, the less will be the declivity of the bed.* But the velocity of rivers which unite augments nearly in proportion to the quantity of water with which they are increased, as has been stated in the preceding chapter. These two rules, then, will finally resolve themselves into this single one: namely, *that the slope of the bottom in rivers will diminish in the same proportion in which the body of water is increased.* This proposition may be established with yet greater certainty by the other arguments which we have used before: since, the relative gravity being proportional to the sines of the inclinations of the planes, if the sine of the inclination of the bottom in the recipient, after the junction of the tributary, were diminished in proportion to the quantity of water with which it is increased, the accelerating forces, and the successive

accelerations, which are caused by the slope of the bottom, would also diminish in the same proportion. But the whole velocity of running waters, on the concourse of a tributary, increases in proportion to their quantity, at least nearly and sensibly so. Then, if the sines of the slopes of the recipient, before and after the junction of the tributary, were reciprocally proportional to the quantities of water, the total and absolute velocity, after the confluence, would be greater than before it, and the force would be greater also; whence it results, that the sediments would float so much the better, and that the bottom of the united waters must even be further excavated. Therefore, in lessening the sine of the slope, on which the bottom of the solitary recipient is established, in proportion to the quantity of water by which it is increased, there would be obtained a slope greater than is necessary for the body of the united waters.

But to remove all common hydraulic doubts and difficulties, we will still further endeavour, on this occasion, to establish the truth of this theorem by the observations which we have made on the slopes of rivers. The quantities of water in the Samoggia united with the Lavino, and in the Samoggia alone, being nearly as 4 to 3, according to the results of the preceding chapter, and the reduced slope of the Samoggia, above the entrance of the Lavino, throughout the whole space where there are no stones or gravels, being 53 inches 5 lines per mile; if the sines of the slopes are diminished simply in proportion to the quantity of increased water, the slope of the Samoggia, below the entrance of the Lavino, will be 40 inches, and, according to the last taken levels, it was found to be precisely 37⅓ inches. Thus, although the

bottom of the Samoggia is irregular, it appears that, in its reduced slopes, it nearly agrees with the preceding rule. The small difference existing between the calculation and the observations may be readily attributed to the diminution of slope that necessarily takes place in the Samoggia, even whilst it remains solitary, when once it has passed the last limits of the gravels, which are about the confluence of the Lavino. The bottom of the Reno is more regular, and it carries more uniform substances, both above and below the entrance of the Samoggia. The volume of the Reno alone is, to that of the Reno increased by the Samoggia, about as 7 to 5. If you diminish the sines of the slopes in the aforesaid proportion and if the slope above the entrance of the Samoggia were 25 inches, this slope would be below the entrance $17\frac{6}{7}$ inches; and if you reckon the slope at 26 inches 2 lines, it would be $18\frac{4}{7}$ inches. Now, the slope of the Reno, a little below the confluence of the Samoggia, is $17\frac{2}{3}$ inches, and in all the lower space, as far as the breaches, its reduced slope is $18\frac{1}{3}$ inches.

Thus, observations agree with the rule, as far as can be expected in matters of this sort. It is a mere fact; and the fact may throw light sufficient to enable us to conjecture what would happen in case the Savena, the Idice, and the other inferior torrents, were to be united to the Reno; and how Nature would operate in other cases, and under similar circumstances. One may venture, then, to assert, that *the bottom of the recipient will be equally established above and below its junction with a tributary, if the sines of the slopes are reciprocally in proportion to the quantities of water.*

CHAPTER VI.

OF THE SLOPES IN THE LAST TRUNKS OF RIVERS.

NATURE, as if in sportive mood, exhibits a singular phenomenon in the lower trunks of rivers, when they are about to discharge themselves into the sea by spreading their waters over its surface. At a considerable distance from their mouths, they establish themselves on a bottom of a very small declivity; but, much nearer the mouth, the bottom which had bent downwards, again rises, and thus forms a deep concavity.

The celebrated M. de la Condamine, in the account which he has given of his voyage, reports, that, *in the great river of the Amazons, the flowing and ebbing of the ocean were observable at a greater distance than two hundred leagues from the mouth of the river;* which is as much as to say, that in all that space the bottom of the river is lower than a horizontal line drawn from the surface of the sea at low water. I have also observed, in the Thames, that the flood tide is discernible as far as ten miles above London. The same thing happens in the Meuse, and in other rivers where the tides run far up. It is at Lagoscuro that the bottom of the great Po is first perceived to be lower than it is at its mouth. The level of the surface of the Mediterranean, when it is lowest, meets the bottom of the Tiber at the distance of fourteen miles

from its mouth ; and in this last space, this same bed is seven feet lower than at the mouth. Although the Lamone carries but a small stream, and has great shoals in its upper districts, yet, in the last mile, it is considerably sunk below the depth at its mouth. The bottom of the river Savio, for the space of the two last miles, is below the horizontal line drawn from the surface of the sea at low water, and then rises towards its mouth, at which it is not above three feet in depth. The same phenomena, in a proportionate degree, are observed at the mouths of the Adige, of the Arno, and of the Ronco united with the Montone. The bottom of the Primaro, at the distance of about sixteen miles from its mouth, at the place called Longastrino, is nearly eight inches below the level of low water mark in the Adriatic, and about four feet above the depth at its mouth. For the space of three miles and a half from Longastrino to beyond the entrance of the Santerno, the slope of the bed of the Primaro is about 7 inches per mile, and for the next three and a half miles, at the rate of 4 inches, even in the vicinity of the entrance of the Senio. Below that entrance, the bottom of the Primaro is beneath the horizontal line drawn from the lowest point of the mouth, and forms a concavity, which, reduced, may be reckoned at 2 or 3 feet.

Guglielmini, in the fourth Proposition of his ninth chapter, has been the first to observe, that in those parts where the floods and ebbs are very great, the water of the sea, which, during the flood enters into the bed of the rivers, returning back with the ebb, help to clean out the bed, and to sweep away the deposits. He has repeated this doctrine in other writings, where he has said, that *so long as rivers could, of themselves, keep their mouths open on a flat shore*

the regurgitations of the tides would prevent any shoals from forming in the trunk lying above the mouth. M. Gabriel Manfredi, the worthy brother of Eustace, himself a great algebraist, and well versed in all that concerns the management of rivers, both in theory and practice, has observed, that this is precisely the case with the Primaro, which, even after the introduction of all the turbid contents of the Idice, has kept its mouth about four feet and a half, at low water, below the level of the sea, as it was in the end of the last century; and then, comparing together the observations, which had been made from the end of the last century to the middle of the present, he has found, that the bottom of the Primaro has undergone no material alteration, from the entrance of the Santerno to the sea; and, arguing from past experience to what might be expected hereafter, he has proved that the flux and reflux of the sea, and the fall of three feet, which the bottom of the Primaro has at its mouth, above the depth of the mouth itself, are sufficient to prevent any apposition, so fixed as to obstruct it, from being formed in all the lower space. Finally, he has explained the ideas of Guglielmini, and has reduced them to the following principles, which are very plain: that the constant submersion of the whole bottom, below the level of the lowest ebb, which arises from the invariability of the river's mouth, must preserve the deposited matters always detached and saturated with water; that the current of the flood tides must keep them raised from the bottom; and that this current, setting against the stream of the river, must raise its surface two or three feet more than the ebb tides require; and thus the current of the ebb, being much stronger than that of

the flood, must always contribute to increase the agitation of the particles of the water, to keep incorporated with it the sediments which alone reach the mouth, and to prevent their settling, and thereby raising the bed. It is certain, that, although the two currents may not be very violent, and the difference of their motions may not be very great, they cannot but contribute in some degree to preserve the sands, &c., in a state of suspension, in the same manner as any increase of motion in the water that had imbibed them would do.

On this particular subject, I added, in the first edition of this treatise, another important reflection. The theory of rivers flowing through sluices may, in a certain degree, be applied to the mouths of rivers, which being, at the height of their floods, raised several feet above the level of the sea, spread themselves freely over it. The freeness of the course, and of the outlet, ought to give increased velocity to the stream, and the greater acceleration should necessarily occasion the lowering and excavation of the bottom through the whole of the upper space, as happens above the openings of sluices. Neither the cause, nor the effect, of this increased velocity can be doubted, because the surface of rivers, which in the more distant parts flows parallel, or nearly so, with the bottom, inclines downwards and approaches nearer to the bottom in the vicinity of their mouths. This striking phenomenon has already been observed and noticed by Father Castelli, in his fourteenth Corollary on Running Waters. In the Primaro, the greatest inclination of the surface is perceptible to the distance of three miles and a half from its mouth. So that, in applying to the lower trunks of rivers the general theories of dams, as we

have explained them in the third chapter of the first Book, and beginning to draw the slopes from the place where the augmentation of the velocity, which arises from the freeness of the fall, begins to be insensible, I evinced, that the line of the bottom of the Primaro, even in the case of the union of all the waters of the Bolognese, ought to commence at the distance of about three miles and a half from its mouth. I did not deem it requisite to begin the slopes higher up, because in the three following miles, in ascending the Primaro, till near St Albert, the high surface of the water flows visibly parallel to the bottom of the river. And as the last concavity, by means of which the bed comes to be lower than the horizontal line drawn from the bottom of the mouth, extends to the vicinity of the Senio, and occupies a space of eight miles, I was of opinion, that this concavity ought to be attributed partly to the acceleration of the stream, and partly to the action of the flux and reflux of the tides, which are very sensibly felt at this place.

Eustace Zanotti, the celebrated professor of astronomy in the University of Bologna, in his excellent Dissertation on the Disposition of the Bed of Rivers near their Entrance into the Sea, is of opinion that the Primaro, in its actual state, having in many parts no embankments, and not receiving all the impulse which the body of the united waters would require, could not serve as a rule for what might be expected to happen when all the waters were united in it, and retained within embankments. Then, on examining the instances of those rivers that are better regulated, and considering attentively the very correct profiles which we possess of the Po and of the Tiber, he concludes, that, in these rivers, the acceleration of the

waters, occasioned by the freeness of the outlet, extended up the river to a considerable distance, and reached to the spot which would be struck by a horizontal line drawn from low water mark. Finally, on comparing these observations together more in detail, he discovered, that the reduced slope of the surface, in the highest floods, reckoning from the point, to which the surface of the sea at low water reaches, to the mouth, was equal to the reduced slope of the bottom, or of the lower superficies of the river, beginning from the same point, and proceeding in the opposite direction. If this rule must likewise operate in the Primaro, in case the waters were all united in it, and if the slope of the surface, reckoning down the river from the point that would be reached by a horizontal line drawn from the surface of the sea at low water, ought to be equal to that of the bottom in ascending the river; supposing the slope of the bottom to be one foot per mile, and the height of the floods to be sixteen feet, the length of the bed, which in this case would remain below the horizontal line drawn from the surface of the sea at low water mark, would be sixteen miles, and the space where the regurgitation would be perceptible would be nineteen miles, on the supposition that a slope of ten inches per mile would suffice for the united waters of the Reno and the other inferior torrents.

If one would certainly know what will happen in future, independently of every sort of theory, it will be necessary for him attentively to consider the past. Towards the end of the year 1749, they introduced into the Benedictine Canal, and into the Primaro, the waters of the Idice, enclosed between embankments on every side, but very little assisted by the waters of

the Reno, and of the Savena, which spread themselves by their breaches over the valleys higher up. The sluice, which had been placed at the mouth of the Idice, was soon carried away; and the bottom of this torrent lowered itself for the space of ten entire miles, as far as to the other sluice della Riccardina. This depression was eight or nine feet at the mouth, and two at the sluice della Riccardina, as the people of the country have assurred me, and caused an enlargement of the bed, in some places by a third, in others by a fourth, which interrupted the road for carriages upon the free-sides. All this mass of substances, torn up from the bottom and the sides, and added to the slime and mud generally swept down by the Idice, must have composed a body of water far more turbid, and requiring a much greater slope than that on which one might establish all the united waters of the Bolognese, while carrying only their common sediments. We have then had a case evidently more unfavourable than any that can hereafter be expected to happen. Let us observe what were the consequences. After the introduction of the Idice, and all the accidents which we have just now enumerated, the Benedictine Canal filled up, and the whole bottom of the Primaro was considerably raised as far as Longastrino. From the church of Longastrino, to the vicinity of the mouth of the Senio, the present bottom of the Primaro has not sensibly altered since 1739, before the construction of the Benedictine Canal. In the two first miles below the same church no alteration has been observed, either from 1739 to 1757, or from 1757 to 1761. In the next mile, as far as to the junction of the Santerno, and for half a mile lower down, the bottom of the Primaro rose between 1739 and 1757;

and it lowered itself nearly as much between 1757 and 1761, as is manifest from the profiles. In the three or three and a half miles that follow, as far as to the entrance of the Senio, the bottom fell from the year 1739 to 1757, and raised itself again nearly as much from 1757 to 1761. Thus, for more than twenty-two years, the bottom is found to be nearly in the same state as before, in the space of seven whole miles above the opening of the Senio into the Primaro. In the nine last miles from the Senio to the sea the bottom is raised below the mouth, but has sunk a little lower down, and then, at another place still lower down, it has risen from 1739 to 1757; so that, taking the elevations with the excavations, it cannot be said that the bottom has in all this time undergone any considerable change. From 1757 to 1761, certain moderate floods had occasioned some uniform heightening of the bottom, but these having been succeeded by a violent fresh, in November 1762, on measuring anew the sections of the Po, at the same spots, it was discovered that the whole bottom beyond the entrance of the Senio was considerably lowered.

The inference from these facts affords us sufficient light to prognosticate, on good grounds, what may be expected to happen, if all the torrents of the Bolognese and of Low Romagna should be united with the Primaro, provided the necessary precautions were taken to prevent their sweeping suddenly, from the bottom and banks of their own beds, into the common channel, a quantity of substances greater than they usually sweep in the time of floods. In the first place, if, since 1693, when the first survey was made at the visit of the Cardinals d'Adda and Barbarini, to the present period, the depth of the mouth has not been

diminished, it cannot reasonably be apprehended that all the waters, when reunited in the Primaro, would not for the future preserve their course into the sea equally free. Secondly, if by the acceleration of the waters at the mouth, and by the action of the flood and ebb tides, the concavity, which extends from this very mouth upwards as far as to the Senio, and through which the bottom rises as it goes on towards the sea, has preserved itself ever since the introduction of the Idice into the Primaro, there will be still less reason to fear the formation of any permanent and sensible appositions, if a body of water much greater, and comparatively less turbid, than that which now flows therein, were to be united with the Primaro. Thus, if the slope of four inches per mile, which the bottom has from the Senio to the Santerno, and of seven inches, from the mouth of the Santerno as far as to Longastrino, with the depth of the bottom at that place, at least eight inches below the low-water mark at the sea, joined to the action of the flow and ebb of the tides which are perceptible there, have maintained, until now, all the physical invariability that a river can possibly have; there is room to believe that the sediments may be still more easily detached from the bottom, when, to the force of the same returning waters, and to the same depth, as well as same slope of the bottom, there shall be superadded a considerable body of water, and the acceleration arising from the free opening into the sea shall extend, perhaps, far beyond its common and present limits. On the strength of these suppositions, there is reason to believe, that, in uniting all the waters, and regulating them in the Primaro, no slope of the bottom from the Senio to the sea would be requisite; and that, in re-

turning backwards from the Senio to the Santerno, the slope of four inches per mile would be sufficient, as well as that of eight inches from the Santerno to Longastrino. From Longastrino upwards, as the flood and ebb of the sea, and the acceleration of the stream, are no longer perceptible, one must begin to fix the slopes according to what the volume of the whole river, and the minuteness, greater or less, of its sediments, may require.

CHAPTER VII.

ON THE DISTRIBUTION OF THE SLOPES OF RIVERS.

Taking the flow of the Reno, and of the other inferior torrents, as it was given towards the end of the second chapter of this Book, and supposing that the slope of the Reno alone, which is $14\frac{3}{4}$ inches per mile, ought, in consequence of its union with these torrents, to be diminished nearly in proportion to the increased quantity of its waters; the slope of the Reno would be, after its junction with the navigable canal and with the Savena, $12\frac{5}{6}$ inches; after the confluence of the Idice, $11\frac{1}{6}$ inches; and only $9\frac{3}{4}$ inches when the addition of the Centonara, the Quaderna, and the Sillaro has been effected: as appears from the Table annexed to this chapter. The only objection that might be made against this diminution of the slopes, which is principally founded on the instance which has been observed at the confluence of the Samoggia and the Reno, would be, that as the floods of the Samoggia, and of the Reno, often come down at the same time, and the floods of the inferior torrents very seldom occur at the same period as those of the Reno, one cannot, from what has taken place in the Reno and the Samoggia, establish a certain rule whereby to fix the diminution of the slopes. But, in the first place, the floods of the Savena, and of the other inferior torrents, will precede those of the Reno by a much shorter

period, if the waters of that river were no longer to spread themselves over the valleys, but were to flow in one united channel from the breaches into the Benedictine Canal. Secondly, it is proper to remark, that all the torrents of the Bolognese derive their origin from situations not greatly distant from each other; and, that there is no great difference in their courses. Hence, allowing that their freshes are principally occasioned by general causes, such as rains and melted snows, it is not possible that the Reno, when flooded, should meet these torrents entirely empty. These facts once established, and admitting that the Reno, in its floods, contains 140 parts; the Savena, together with the navigable canal, 22 parts; the Idice, 24 parts; and the other inferior torrents, 25 parts; we are not so daring as to form a disadvantageous hypothesis, while we suppose that the floods not occurring at the same time in all, the Saveno will add to the Reno only 10 parts, the Idice 12 parts, and the other inferior torrents 15 parts. On this hypothesis, the falls would be, to the Saveno, $13\frac{4}{5}$ inches; to the Idice, $12\frac{3}{4}$ inches; and $11\frac{2}{3}$ inches to the confluence of the other torrents. Lastly, supposing the greater floods entirely out of the question, and that the medium floods, or a quite different state of the Reno, were alone considered, and that, for example, the Reno were allowed to contain only 70 parts, the Savena 5, the Idice 6, and inferior torrents 7 or 8; the proportion of the quantities of water, and of the sines of the slopes, would be always the same, according to what we said above,—namely, that if the recipient, when alone, establishes itself on a given slope, both when its waters are low, and when they are high, and when they are in their medium state, it

will, after the junction of other streams, require a less slope to keep the incorporated sediments at all times suspended, and to detach the deposits from the bottom.

However, to take into the account not only the increase of the waters, but also the attenuation of the sediments, it is to be observed, that the Reno, at the breach Panfilia, floats down larger sands than either the Savena or the Idice can naturally convey to their openings into the Benedictine Canal. Yet, if the Reno were confined and retained between embankments, and should flow on to meet the Savena in that canal, it is certain, according to what has been stated, that, after eleven miles of distance, the sands must be considerably more attenuated, and become, at least, nearly similar to those of the Savena and of the Idice. It is true, that, after the ruin of the sluice of the Idice, this river floated, even into the canal, some coarser substances, and even some small gravels; but these substances had been torn up from the bottom, and brought down from the higher parts of the river, in consequence of the depression and enlargement of the bed of this torrent. The proof consists in this, that in the ancient bed of the Idice, near to the Benedictine Canal, and in the last trunk of the Savena which is equally abandoned at present, neither pebbles nor large sands are discovered. Therefore, if the bottom of these rivers is not still further depressed, the Idice, the Savena, and the Reno, together, will convey substances into the Canal, nearly in the same quantity, and of nearly the same quality.

This conceded: in the first place, it cannot be doubted, that, if the Samoggia, whose slope is three feet per mile, in uniting itself with the Reno, dimin-

ishes the slope of that river, and from 25 or 26 inches reduces it to 18, the waters added by the Savena, the Idice, and the other torrents, which are neither less copious nor less turbid, must reduce the slope of the common bed, not only below three feet per mile, which is what is required by these tributaries in their own beds, but even under that of 14¾ inches, which the Reno itself has above the breach. It is certain, in the second place, that if the waters of the Reno flowed in a united stream from the breach to the canal, they would, after a course of eleven miles, and before they reached the Savena, cease to require any slope that was not considerably less than 14¾ inches, in consequence of the attenuation of the sands and the other substances; and that if the Reno, when it pursued its course to Vigarano, six or seven miles lower down than the actual breach, flowed on a slope of 12¾ inches per mile, it would certainly not require a greater slope before it reached the Savena, regard being paid to the diminution of the sediments. The same advantage would exist throughout all the lower space; so that 12 inches might suffice after the confluence of the Saveno; 11 inches after that of the Idice; and 9 or 10 inches to Bastia, where the matter brought down would be still more attenuated, as well in the common bed as in those of the inferior torrents.

Thus, to recapitulate all that has been said, let us suppose that the Reno, its waters being reunited and retained between embankments, is to be conducted from the existing breach into the Benedictine Canal; that the Savena and the Idice are to be joined to the Reno in that canal; and that the canal is to be continued in a direct line to Bastia, whence the whole body of water,

after having been increased by the three inferior torrents, is to go on to discharge itself into the sea through the present bed of the Primaro. The example of what takes place, in the higher parts, to the Samoggia and the Reno—all the observations made on other rivers that can be collected—all the most plausible theories supplied by hydraulics—everything, in one word, tells us, and assures us, that the bed of the Reno being established above the breaches, on a slope of 14¾ inches per mile, 14 inches will suffice after the confluence of the Saveno, 12 inches below the entrance of the Idice, and 10 after the junction of the other torrents, to Bastia; and that, in like manner, below Longastrino, to which the tide extends, 7 inches will be sufficient as far as to the mouth of the Santerno, and 4 inches from the Santerno to the Senio, where the bottom begins to deepen below the depth of the opening into the sea, and at last goes on ascending. We have already shown evidently, that the declivities which we have assigned will be greater than will be required to keep the bottom of the bed well cleansed out, and to prevent any deposits from forming there. It remains now to show, that these slopes will also be sufficient to afford a free passage to the streams of the tributaries, and to secure a certain and effectual drainage for the inundations of the country. I will here enter willingly into the most minute details, not only on account of the importance of the case to which I wish to apply my doctrine, but also because it may happen, that the present example may serve as a rule in other similar cases.

The bottom of the Primaro, near the parish church of Longastrino, is lower than the common horizontal line, to which the last levels were referred, by 1 foot

8 inches and 3 lines. This spot is distant from the Bolognese Canal 3295 perches and 7 feet, which, with a fall at the rate of 10 inches to a mile, would give 5 feet 5 inches 11 lines.* The bottom, then, of the Primaro, at Bastia, towards the entrance of the Bolognese Canal, would be higher than the same horizontal line by 3 feet 9 inches 8 lines, which is very nearly the medium height between that of the Primaro in 1757 and 1761; consequently the Zaniolo, and the other canals of Bastia, will have, on the new bottom, an easier and a more certain issue than they once had at that place; and, moreover, the bottom of the Correchio, which, according to the levels above mentioned, is, at the distance of three miles and a half from Bastia, raised above the common horizontal 14 feet 11 inches 8 lines, will have, from the same place, a fall of about 3 feet per mile on the bottom of the Primaro.

The Sillaro, at the spot where it is cut by the line to which the epithet Upper has been given, is above the common horizontal 22 feet 11 inches 9 lines; and the Quaderna, at the intersection of the same line, is

* To illustrate the calculations in this chapter, as well as in some other parts of the work, the following table of the measures chiefly employed by the author is introduced.

TABLE OF BOLOGNESE LONG MEASURE.

Lines.		Inches.		Feet.		Perches.		Mile.
12	=	1 (*a*)						
144	=	12	=	1 (*b*)				
1,440	=	120	=	10	=	1 (*c*)		
720,000	=	60,000	=	5,000	=	500	=	1 (*d*)

(*a*) = 1·2144 English.

(*b*) = 14·5728, or very nearly $14\frac{6}{10}$, English inches.

(*c*) = 12·144 English feet, or 12 feet 2 inches nearly.

(*d*) = 1·15 English, or 1 mile and 264 yards.

above this horizontal 23 feet 9 inches. Now, the Sillaro, where it flows freely and embanked, requires a fall of 2 feet per mile; and the Quaderna, after its union with the Gaiana, requires $2\frac{1}{2}$ feet; therefore, if you turned off the Sillaro alone to conduct it to Bastia, from the point where it is cut by the Upper Line, by causing it to flow for a course of five or six miles, it would still be 11 feet above the common horizontal, and 7 feet higher than the bottom of the Primaro. So also would it be with the Quaderna, which might flow to and spread itself over the same bottom, although it were carried, without the least variation in the slope, through a track of eight miles, from the point where it cuts the line, to Bastia, passing close on the lower edge of the valley of Marmorta, where the soil has sufficient solidity to admit of its being enclosed and retained between embankments.

Several other expedients might be proposed for these two torrents. In the first place, as at the distance of three miles from Bastia, the bottom of the Quaderna would be higher than the common horizontal by $11\frac{1}{4}$ feet; and the bottom of the Sillaro, by nearly 17 feet; one might throw the Sillaro into the Quaderna, securing its mouth by a sluice, and afterwards conduct these torrents, united, into the Primaro, since, in consequence of this union, the Quaderna would no longer require so great a declivity throughout the lower space, and would there have a freer course. The Guarda and the Menata, which are conduits of water lying between these two torrents, are, at the distance of six miles from Bastia, higher by about $15\frac{1}{2}$ feet than the common horizontal, and require a slope of about six inches per mile; whence it follows, that, in the event of the union of the two

torrents, these two conduits might have, at the point of confluence, an opening of two or three feet into the common bed. Besides, in conducting the Sillaro to Bastia, one might unite the Centonara to the Quaderna, and conduct these two torrents together along the left of the valley of Marmorta, where they would meet all the other waters which had been united in the higher parts.

In following the course of the Primaro, and going directly from Bastia to the bend of the Benedictine Canal at Morgone, there are 10 miles and 200 perches; and thence to the entrance of the Idice, 3 miles more and 300 perches. If, in rectifying the Primaro, and conducting its new bed through the stiffest and firmest grounds in the valley of Marmorta, its course were shortened three miles, as we shall point out in the ensuing chapter, there would not remain, from Bastia to the Idice, more than 11 miles, which, at the rate of 12 inches per mile, would give 11 feet; to which, if the 3 feet 9 inches and 8 lines, by which the bed of the Primaro is raised above the common horizontal, were added, the total would be 14 feet 9 inches and 8 lines. But the actual bed of the Idice, at its confluence with the Benedictine Canal, is higher than this very horizontal by 21 feet 8 inches and 8 lines. Therefore, to prevent the Idice from lowering itself still further than it has already done, it would be necessary to secure its entrance into the canal by a sluice of seven feet.

The Centonara requires, in its own bed, a fall of about 3 feet per mile; and, at the point where it strikes the Upper Line, it is elevated above the common horizontal 28 feet 7 inches 8 lines. As this torrent might establish itself on a bottom of a constantly

and uniformly decreasing declivity in the lower parts, it might be conducted by itself into the continuation of the Benedictine Canal, at the distance of about 7 miles from Bastia, and of 5½ miles from the point of intersection. The conduit Corla, being higher than the common horizontal line by 35 feet, at the point where it is intersected by the Upper Line, would always have a free entrance into the Centonara. The Oriolio and the Vena or Vidoso Cut, which are conduits lying between the Centonara and the Quaderna, are, at the point where they are cut by the line called the Middle Line, higher than the common horizontal by 11 feet: as they are only small runs, they cannot require any considerable slope, and might, therefore, have a free issue into the proposed continuation of the Benedictine Canal.

Between the mouths of the Zena and of the Idice, there are only 541 perches, which, at the rate of 14 inches per mile, would give 15 inches 2 lines. From the Zena to the rivulet of Brughieres there are 374 perches 3 feet, and from this rivulet to the Savena 577 perches 7 feet, which would give 10 inches 7 lines, and, 16 inches 2 lines. The bottom, then, of the Benedictine Canal, at the entrances of the Zena, of the rivulet, and of the Savena, would be higher than the common horizontal, respectively, by 16 feet 10 lines, and 16 feet 11 inches 5 lines, and 18 feet 3 inches 7 lines. The opening intended for the Zena, when the Benedictine Canal was first constructed, and which could not be carried into effect on account of the filling up of that canal, is higher than the common horizontal by 16 feet 5 inches and 10 lines. It follows from what has been said, that, as the falls which we have assigned are greater than those which

would be required, and the outlet for the drains is capable of being secured against the overflow of the floods by means of a regulator, one might easily, in executing the project for the continuation of the canal, give a free entrance to all the drainings, without being obliged to pass them under the bottom of the Idice by subterranean aqueducts, which, however, one might also always open without difficulty. The mouth of the rivulet Brugghiate is elevated above the common horizontal by 20 feet 2 inches 5 lines, so its opening would be more free and secure. The bottom of the Savena, at its entrance, is above the horizontal line by 21 feet 11 inches; and at the pass of Teddo, at the distance of four miles and a half, it is higher than it is at the entrance by nearly 17 feet; so that the Savena would flow with facility in its last trunk on a slope of 3 feet per mile, and would have at its mouth a fall of 3½ feet.

From the Savena to the Lorgana there are about 350 perches, which require 9 or 10 inches of declivity. The bottom of the Lorgana is above the common horizontal 20 feet 4 inches; consequently, this very bottom would remain higher than the bottom of the recipient by more than one foot. The Riolo would also have a free entrance, seeing that the bottom of its last channel is raised 4 feet 1 inch and 2 lines above the actual bed of the Salarola, at the distance of 5 miles. It would be the same with the Navigable Canal, and the navigation would be secure to the Salarola, and to the pass of Segni. Lastly, the bottom of the Reno, at the breach of Panfilia, is 37 feet 7 inches and 7 lines higher than the common horizontal. By not reckoning the slope of the Reno for the first mile above the breach, where its bed has

lowered itself, the declivity for the other miles is at the rate of $14\frac{3}{4}$ inches, as has been stated, and as is proved by old levels very carefully taken by stagnant water. Although, therefore, the Reno were still to flow on the same slope to the Savena, a space of $10\frac{4}{5}$ miles, this elevation would always exceed that which is requisite, and the bottom of the Reno would lower itself some feet, if it were not kept up by a sluice.

It follows, from all that has just now been said, that the slopes which we have assigned would not only be fully adequate to preserve the bed well cleared from all deposits, but would also suffice to grant a free entrance to the inferior torrents, and to the drains of the country lying between them.

	Sections.	Reduced Breadth.		Greatest Height.		Velocity of the Surface per hour.	Quantity of Water passed in one Second.		Quantity of the United Waters.	Slopes of the Bottom.
		Feet.	Inches.	Feet.	Inches.	Inches.	Cubic Inches.	Arith. Means.		
The Lavino, alone, . .	Section Q. Section P.	44 44	528 528	7·8 9·10	92 118	180,000 180,000	8,219,112 11,844,043	10,031,577	39,580,699	
The Samoggia, alone,	Section O. Section N.	53½ 58	642 696	12¾ 18	153 216	180,000 180,000	21,085,741 38,012,504	29,549,122		
Samoggia with Lavino,	Section K. Section M.	70½ 82½	846 990	15⅔ 17	188 204	180,000 180,000	37,641,360 42,468,495	40,054,927	139,904,865	
The Reno, alone, . .	Section I. Section G.	176 151	2112 1812	17½ 16½	210 198	210,000 210,000	111,749,323 87,950,554	99,849,938		14¾
The Navigable Canal,	...	...	240	...	60	90,000	...	1,934,171	141,839,036	
The Savena, . . .	Section XXIII.	64½	744	12¼	147	210,000	...	20,806,109	162,645,145	12⅝
The Idice, ...	Section XXI.	67½	810	12	144	210,000	...	24,682,860	187,328,005	11⅛
The Centonara, . .	Section XVII.	20	240	4¼	51	180,000	...	1,594,600	188,922,605	
The Quaderna, . .	Section XII.	36	432	8½	102	180,000	...	7,831,188	196,753,793	10½
The Sillaro, . . .	Section X.	60	720	9⅚	118	180,000	...	16,150,920	212,904,713	9¾

BOOK III.

ON RIVERS THAT CARRY SANDS AND MUD.

CHAPTER I.

ON THE OLD BEDS OF RIVERS.

TACITUS relates, in the First Book of his Annals, that, when a proposition to turn off all the rivers which flowed into the Tiber was made in the Roman Senate, although the importance of the object, and the necessity of applying a remedy to the but too frequent inundations of a city at that time the capital of the world, appeared amply to justify the plan, yet, after they had heard the reclamations of the provinces interested in the measure, the opinion of Piso was adopted: who advised, that no alteration should be made, since every one might perceive, that *Nature had known how to provide for our wants much better than Art, in assigning to rivers those springs, courses, boundaries, and limits which were the most apposite.* Father Grandi, in his Dissertation on the Project of giving a New Course to the Era, begins with this ex-

ample to demonstrate that the plan for repairing and strengthening the ancient bed of this torrent was preferable to the scheme of making a new one. He supports his opinion by two other examples from the celebrated Viviani, who, in making a new bed for the Sieve, had followed the limits of the ancient bed of the waters; and had observed the same caution with respect to the Bisenzio, following the traces of the ancient bed, and straightening it only at one spot, where it formed a long and winding sinuosity. This method has generally been followed in similar cases.

Cornelius Meyer, a celebrated Dutch engineer, in a manuscript Dissertation, now in my possession, on the Method of Preserving the City of Pisa from the Inundations of the Arno, disapproves of all the proposals for changing the bed of the river, and restricts himself to a proposition for improving and aiding the mouth, raising and strengthening the side-works, correcting the deviations, and straightening the principal sinuosities of the old bed.

M. Geneté has followed of late the same maxims in Holland, disapproving, as we have before said, of all the new cuts and deflections which had been devised, and proposing in their room to reunite all the waters of the Great Rhine in the ancient branch of the Issel, which should be made straight, and brought to an uniform breadth; thus seconding Nature, which unites and so conducts all waters to the sea.

The same passage from Tacitus is quoted by Guglielmini as the conclusion of his advice to suffer the Reno, and the other waters of the Bolognese, to flow towards the north, and into the lower parts of the country, in preference to forming a new bed for them, towards the east, by other higher lines. He remarks,

that in reflecting on the directions taken by the streams of Lombardy and Romagna across the valleys, and on the courses they have naturally chosen in flowing through the plains, one perceives that all these courses are from the south towards the north: an evident indication, that it is the wish of Nature to send them to an outlet which points to their north, and not to their east; and that to attempt to turn all these rivers towards the east would be to commit an act of violence against Nature, in itself attended with considerable risk, and, moreover, very expensive. In proof of his assertion, Guglielmini has adduced all the ancient and new levels; from which it appears, that the plain of the Bolognese does really slope towards the north and the east, but more towards the north than it does towards the east: and to give a physical reason for this fact, he says, the Bolognese plains have been formed by the alluvions of rivers, and have thus followed the declivities of their beds, in sloping more towards the north than towards the east, and more towards the east and the sea than towards the west, because the streams of the rivers which lay more easterly, being nearer to their termination, could not elevate themselves so much as those which lay more towards the west. From this he concludes, that the plains of the Bolognese, and of the Romagna, are not, in their higher regions, adapted for admitting and retaining the rivers within banks, in case they should be turned eastward; because, to produce this effect, it is necessary that the alluvions should have been formed while the waters were conducted straight to the sea, and not while they were permitted to flow, from the south to the north, towards the Po di Primaro.

All these principles have been followed in the celebrated Opinion of the Cardinals d'Adda and Barberini, which was drawn up under the eyes of Guglielmini and Viviani. As it was then decided to conduct the Reno into the Great Po, they adopted the scheme of collecting into the Primaro all the other torrents and inferior drains: for the valleys of the Bolognese, from the sediments that had been deposited, were almost reduced to the state of simple low meadows; and the torrents opened up in them, for themselves, such roads to their openings into the Primaro as they were permitted to do by the nature and situation of the ground; so that it only remained to assist Nature, and by Art to second her endeavours to direct and regulate the course of the waters. But when, at the commencement of the present century, the hope of reconducting the Reno into the Great Po was given up, Guglielmini explained more fully the only plan that remained practicable: namely, to unite all the waters of the Reno, and of the other torrents and drains, in the Primaro. He pointed out also the method that ought to be observed in the management of this work: which was, first to make the Lamone enter the Primaro, and afterwards to begin and form the beds of the Senio, and of the Santerno, carefully observing what lights might be procured from the effects which they produced, and so to proceed step by step to the other higher torrents. What has been the consequence? As they did not turn the Lamone from its actual bed, its bottom, since the days of Guglielmini, has risen higher and higher; so that very high embankments are required to retain its great freshes, and it frequently, by bursting its banks, occasions great damage to the neighbouring countries. On the other side, the

good effects that were observed when the Senio and Santerno were conducted, well secured by embankments, into the Primaro, confirm the opinion of Guglielmini, and are strong inducements to proceed to the formation of beds for the torrents of Marmorta, for the Savena, and for the Reno.

At present, on considering the profiles of the different Lines which have been proposed for the union of all the waters, and observing the bearings of the face of the country, the situation of the drains and the course of all the torrents, it is clearly evident that there is no other mode of proceeding. In the first place, the profiles of the upper Lines represent the whole surface as very wavy, and as if divided into so many great shells, in the higher parts of which lie the beds of the torrents, and those of the drains in the lower. On the lower Line of the Primaro the waving is a great deal less, because, the torrents carrying grosser substances in the higher districts, their bottom becomes there more elevated, and the whole plane of the country more unequal, than they are in the lower parts. Hence arises a natural and an insurmountable obstacle in the way of all the upper Lines; for, if it is desired that the new bed should be low enough to receive the drains, it will be requisite to make considerable excavations, and to force all the affluent streams to fall over very high wears. On the other hand, if it were not thought eligible that the bed should be so low, it would not be sufficiently enclosed in the bottom of the shells above mentioned, and there would be no other resource for carrying off the drainings of the country but subterranean aqueducts. This difficulty disappears in the Lower Line of the Primaro, because the declivities assigned in the last chapter would be fully

sufficient to afford a free issue to all the drainings, and the greatest sluice, that which would be required at the mouth of the Idice, would be only seven feet deep: nor would there be the embarrassment of great excavations, either to carry off the alluvions of the Idice, or to continue the Benedictine Canal to Bastia; which sufficiently shows, that this project is that of Nature.

As far as the actual course of the waters is concerned, it does not appear that any other mode can be adopted. The waters of the Reno, bursting through the breach of Panfilia, flow principally towards the ditch of Passardo, which lies almost in the same direction with the breach, the Common Navigation, and the Benedictine Canal. The higher valleys of the Reno have been for a considerable distance raised and improved, and there is reason to expect, that ere long they will be entirely filled up, and that the Reno will reach the Benedictine Canal with all its ordinary sediments; for, as the Reno finds, from the breaches to that canal, a more than sufficient slope for the discharge of its waters, it must gradually form itself a bed among its own alluvions; and it cannot possibly fail to produce the same effect throughout the continuation of the ditch of Passardo. Thus the valleys of Galliera and of Poggio will in a short time be screened from the expansion of the floods, and the Reno, then entering with its united waters, and its sands and sediments, into the valley of Malalbergo, and spreading itself over a very ample receiver, will, in the course of a few years, naturally fill it up, in the same manner that several other lands in Tuscany and Lombardy have been filled and raised. This is an operation already planned and arranged by Nature;

and if she is aided by the assistance of Art, in directing the course of the waters, and avoiding too great sinuosities, there would be, in the end, only one single bed, continued regularly from the breach Panfilia to the Benedictine Canal. But nothing could more effectually contribute to the speedy melioration of the valleys, and to the complete formation of a continued bed for the Reno, than the carrying of this very canal to the highest point of perfection.

We have already noticed the principal accidents, which happened during the execution of this work, and which have given occasion to so many expostulations on the part of the provinces interested in the subject: namely, the deposits left by the depression of the Idice, and the breaches opened in the dike of the valley of Gandazolo. At present, that valley is so consolidated by the successive deposits of the Idice, which flows back upon it, that there would be no difficulty in crossing it by a straight enbankment that should effectually retain the whole body of the waters. The appositions left by the Idice might be removed, and the expense of excavation be spared, by employing the agency of Nature in the manner pointed out by Michelini, and put successfully in practice by Father Castelli, in the plain of Pisa, at the mouth of the Dead River. This is done by digging in the bed, where the appositions are formed, either several ditches running parallel to each other, or one single cut, proportionably larger and deeper, through which the waters may flow, and, in times of great floods, sweep away all that requires to be removed.

I have seen this method practised with success in places where the fall was considerable, although the

matter which had been left behind was very coarse, and in great quantity. The Serchio having some years back spread itself over the plain of Pisa, and filled its former bed with sands and gravels quite up to the level of the country, its stream, by means of some defensive works that were made in the new bed, and some small channels cut in the old one, was compelled to return within its ancient limits; all the substances deposited were carried into the sea, and the whole disorder was entirely rectified by one great fresh which swept all before it. Now, as it is evident, that if the Benedictine Canal were carried on straight to Bastia, the fall would be considerable, it is thought, that it would not be necessary to remove by manual labour all the accumulations that have been formed in the bed, or to construct it on the slopes which might appear suitable. But, the aggregated materials being once removed, either in the one way or in the other, and the cut being completed, the Reno, the Savena, and the Idice, would have there a free passage, and all the intermediate drains of the country a sure outlet.

As this canal runs almost in the same direction with the trunk of the Primaro below Bastia, it appears once more as a plan pointed out by Nature, that the great and irregular sinuosities of the upper bed of the Primaro should be avoided by continuing the cut to Bastia, and leading into it the Centonara, the Quaderna, the Sillaro, and all the intervening drains. The valley, which takes its name from Marmorta, towards Rovera and the Canal of Beccara, where the prolongation of the cut might be effected, presents a soil sufficiently stable and secure, since carriages pass freely, and it is in summer entirely dried up, and

dusty. Its bottom is formed of flints and very fine sands, as has been ascertained by digging and searching with borers. It has so much consistency, that it requires great force to thrust down a pointed stick one foot. These observations were made by a scientific man, and by some countrymen of great experience. Not a doubt remains, therefore, that the valley of Marmorta, although marshy in other places, may in the narrowest part, and at the place above called Rovera, be excavated, and that dikes may be there solidly established. The straight lines by which the Benedictine Canal might be carried across this valley would form very obtuse angles with each other, and cut off exactly three miles of the course which the waters actually run in the Primaro. And, lastly, the surface of the country is sufficiently raised to permit the bottom of the new bed to be encased in it some feet, and to give every reason to hope, that this part of the work would perfectly succeed.

It is not to be expected that we should here reply to all the various objections which have been started against this project in so many writings, and which time and reflection have already removed from the minds of several persons. We in this place, from a motive of pure esteem, reply only to what has been asserted in the fourth Article of the Second Part of a Report made by three learned men, who, having inspected the lands injured by the floods, and adopting nearly the same plan, have not thought it expedient to follow it in that part which relates to the prolongation of the Benedictine Cut. In the first place, as these learned gentlemen have laid a stress on the loose nature of the soil, we may be permitted to oppose to their simple assertion the authenticated experi-

ments made with boring-rods and sharp-pointed sticks. Secondly, we add, that the length and the irregularities of the Primaro, the obstructions caused by the sinuosities and deflections that are encountered in proceeding from Morgone to Bastia, and the accumulations which have followed the introduction of the Idice, will always expose the lower portions of the Polesine of Saint George to greater risks than if, in following the principles laid down by Guglielmini in the last chapter, the works had been readjusted, and the proper shortenings made. Thirdly, the three feet of fall that would be gained by going straight to Bastia are precisely what would be sufficient to secure an outlet for the drains, and to supersede all the subterraneous aqueducts proposed by these learned men, which, by their number, and the magnitude of their dimensions, would prove very expensive, and of which, moreover, the success would still be very doubtful. Finally, in consequence of the saving in regard to the aqueducts, the scheme of prolonging the Benedictine Cut for the space of seven miles would not be more expensive, on the whole, than that of retaining the Primaro between dikes for ten entire miles; and even granting that this plan would be a little more expensive, the disadvantage on the score of economy would be amply compensated by the physical security of the Polesine.

Another advantage would arise from the proposed continuation of the Benedictine Canal, which is, that from the ampleness of the declivity, the clearing-out, of which the Cut at present stands in need, might in part be spared; whereas it is very doubtful whether this could be effected, if, when the course was extended, the fall, and thereby the velocity of the current,

were at the same time to be diminished. The valley of Marmorta would be better secured by this plan; because, on the left, the Primaro would then serve as a drain for the valley, and not, as is now the case, to lay it under water during floods; and, on the right side, the three torrents that spread their waters freely over it at present would, by means of the greater fall, be conducted more securely in the Primaro to Bastia; and from Bastia to the sea, there is nothing to apprehend, provided the Primaro were made of an uniform breadth, and for the protection of Romagna, and of the valleys of Comacchio, the embankments on the right and left were strengthened and raised to the level of the highest floods. And as several rectifications have already been made in the last trunk of the Primaro, I have proposed to make some others, and to lessen some tortuosities: which would not involve a heavy expenditure; since, to attain the object, nothing would be required but to throw back the embankments for some short distances. I have particularly pointed out two rectifications to be made in places where the windings of the bed are the greatest, and where the valleys of Comacchio are the most endangered by the corrosions: the one at Mandrioles, and the other at Longastrino. In this manner all the damage actually done might be repaired, and there would be, from the breach Panfilia and the Benedictine Canal to the sea, a river restrained within embankments, and requiring no other precautions to be taken than what are usually employed with respect to other rivers.

The geographical advantages of the plan here laid down would be, the defence and security of all the Polesine of Saint George, the melioration of the higher

valleys of the Reno, and of the lower valleys of Marmorta, the ready draining of the lands lying between the Savena and the Idice, and a free and well regulated course for all the waters. But these are not the greatest or the most valuable advantages to be derived. The salubrity of the air, which would be restored by drying up the vast marshy wastes now under water, is certainly not the least important point to those to whom the estates in question belong. At present, at Bastia, at Argenta, and in their neighbourhood, it is usual to see prevalent, in summer, long-lasting fevers, the scurvy, swellings of the spleen, and other disorders seated in the lower intestines, and commonly produced by the bad qualities of the water and the air. In some papers which I have written on the filling up of Valdinievole, and on the opening that was made in the forest of Faggianaia, in the vicinity of Pisa, I have explained how stagnant waters and marshes occasion the insalubrity of the atmosphere, and have assigned, as the two principal reasons, the animal and the vegetable putrefactions which they contain. M. Lancisi was the first who observed that, in the vicinity of standing waters, there was always a prodigious quantity of very small insects. Having spread some cloths in some marshy places, against the direction of the wind, he found them at the end of a week covered with cods, and very small eggs of lenticular, spherical, and oval forms. In the height of the summer these eggs are hatched by the heat of the sun, and are transformed into those small insects and butterflies which are always seen about such places, and which dying there, and sinking, by their greater specific gravity, to the bottom, yield a fetid animal smell very pernicious to health. On the other hand, when the

grasses of the marshes and the other vegetables have putrefied in the water, there is separated from them a certain oily substance, which, being lighter, rises to the surface, rendering it sometimes yellow, and emitting very noisome exhalations.

CHAPTER II.

ON THE NEW BEDS OF RIVERS.

As we have already, towards the end of the first Book, sufficiently discussed the new union of the Reno, and all the other streams of the Bolognese, which was proposed to be effected in the highest parts of the country, above the confluence of the Samoggia and the Lavino; it will not be improper to mention, in this place, some other objections which have been repeatedly started against another proposal of a new bed, which was to commence a little below the same confluence, and, in proceeding forwards, to take up and turn the Reno at a place called Malacappa. This is so much the more to the purpose, as these objections, by being of a general nature, may be applied to other similar cases. In the first place, it was stated, that the expense of this new bed, even by the estimates of the proposers themselves, could not possibly be less than three millions: a sum beyond the reach of all the funds of the three Legations. It was said, in the second place, that an enterprise of this character, in which the object was to form a new bed for so many waters, to turn the course of so many torrents, and to provide a recipient for so many drainings, would, by its complication, its difficulties, and its extent, have astonished the Romans, even in the most flourishing periods of the Republic. Thirdly, it was asserted

that, the plan in question being to form a new bed of about thirty-eight miles in length, all history did not furnish an example from which any light might be obtained concerning the method and the order which ought to be followed in constructing the works; for, if it was intended to carry on, at the same time, the excavation of so many various trunks of the bed, interrupted from affluent to affluent, it would be an impracticable undertaking, or at least exceedingly expensive, to draw off, or pump out, the rain-waters, or those of springs: and that especially in those parts of the excavation which were necessarily several feet lower than the surface of the sea at low water. On the other hand, if they began the new bed, and advanced it gradually, by successively admitting the last tributaries, observing carefully what happened, it is certain, that in laying the new bottom on a slope suitable to the mass of the united waters, and commencing with the admission only of the lowest affluents, they would leave in the bed high and continual deposits.

This second method of commencing the whole work at the lower extremity is the only one which can throw some faint light on so dark a subject, as Guglielmini has expressly stated in his last chapter. It deserves, therefore, a more particular examination. Suppose, then, that the new bed is made between the Senio and the Santerno, and that the sole remaining question is, to make a cut for the one and for the other, to turn them from their present course, and throw them into the new channel; no one can foresee, as writes Eustace Manfredi in his reply to Corradi, what extraordinary effects might be produced by two rivers falling perpendicularly on the new bed from the much more elevated bottoms on which they flow, sustained

by sluices placed at their mouths. It might easily happen, that, at the bottom of these mouths, there might be formed two deep pools, which would extend themselves to the foot of one, or possibly of both, of the embankments, and undermine and overturn them. The apprehensions of whirlpools and deep chasms would be still greater at the mouths of the Idice and of the Savena, which, according to the profiles, would fall from a height of nearly fifteen feet; and then, as the Idice, for example, or the Santerno alone, requires a much greater fall than would be necessary for the united body of the waters, and the completion of their union cannot be regarded as an undertaking of speedy execution, it is certain that the last affluents alone, without the addition of the Reno, which is nearly equal to all the rest together, would form continual accumulations in the new bed, and destroy the whole work as fast as it advanced. One may judge of what is likely to happen if the Santerno were to flow, during several years, on a lower level, unaided by the influence of the higher waters, from what occurred when the Lamone was turned from the Primaro. The evils would be still greater in the more elevated districts, where the Quaderna, the Centonara, and the Idice, bring down grosser substances, and where the Idice must flow for some years on a fall of twenty inches per mile, whilst, in its own proper bed, it requires a declivity of more than three feet. There could be no reason to expect that, in the end, on the introduction of the Reno, it would excavate afresh the bed, which by that time would have been filled up, and settle its own bottom on the declivity best adapted to its stream. For, in the first place, it could never make deep corrosions in the bottom without endanger-

ing the sides and the enbankments; and, further, the slope, which would suffice to enable the united waters to sustain their ordinary sediments, would never be sufficient to sweep off the substances deposited and heaped up by the tributary streams.

Not even the shadow of any of these difficulties would be met with in executing the project which has been proposed in the preceding chapter. The Senio and the Santerno have at present a free entrance into the Primaro. The Quaderna, which now spreads over the valleys before it reaches the Primaro, has a fall sufficient for forming a bed to unite it with the other waters at Bastia. If it were required to introduce the Sillaro into the Quaderna, it would fall into it from a height of five or six feet, and finding in the common bed a greater slope than it had in its own, it would there have a free and certain flow. It would be necessary to turn the Idice, the Savena, and the Reno together, from the sinuous trunk of the Primaro, to convey them, in the proposed continuation of the Benedictine Canal, to Bastia; and whilst this work was in hand, the inferior torrents would continue to flow by the ordinary impulse of the other higher waters. The valley of Marmorta, which must be crossed by this canal, is certainly not worse in quality than the valleys of Bonacquisto and Medicina, which would be crossed by the Line of Malacappa; and if, on the adoption of the first scheme, any breach should take place, either in the right or in the left embankment, the worst that could happen would be, that the waters would continue to spread in the valleys that are already inundated. The present embankment of the Primaro would always serve as a counterbank to secure the Polesine of Saint George. But, upon the

second scheme, if any accident should happen towards the forest of Malvezzi, which would be the most critical point in the whole line, and the spot where the new bed would be the least sunk in the earth, and where the fall would be very moderate, the best cultivated lands in the Bolognese would be in continual danger; because, in the new state of things, if a new breach should be made, the waters would be enclosed between the banks of the tributaries and those of the recipient, without there being any possibility of saying either in what time or in what manner this damage could be repaired, or what would be the expense requisite to effect the reparation. Manfredi was right, therefore, in asserting, that, in all schemes of this description, unless the impossibility of a breach is demonstrated, the remedy proposed is worse than the existing evil.

But the most essential difference between the two plans—the one for repairing and straightening the old channels, the other for preparing a new bed for the waters—consists in the different properties of the substances that would be brought down by the floods in both cases. The different surveys, and the observations which have been made by persons of the greatest ability, have finally established, in the best authenticated manner, two facts: first, that, by the plan for a new bed on higher land, the Reno, the Savena, the Idice, the Centonara, and the Quaderna, would be cut by the proposed line, above the last limits of their gravels: secondly, that the Idice and the Centonara at present carry gravels and coarse sands for two or three miles below the point where they would be cut by the line, whilst, in the Savena and the Reno, only very fine sands would descend so far. This is pre-

cisely the case which Guglielmini has examined in his last chapter, where he treats of tributaries which bring coarser substances than are brought by the main river to the point of their junction. He demands two conditions to ensure to such a union a favourable issue: a superabundant fall, and a considerable elevation in the general level of the country: conditions not to be obtained upon the plan of the Upper Line; for if it is kept below the forest of Malvezzi, the bottom of the new bed would be higher than the surface of the country, and the drainings could not possibly enter it, as is clearly shown by the profiles. If, on the other hand, the Line were run above this forest, the bottom would hardly be sunk within the earth, and it would meet the Quaderna two miles above the last limit of its gravels. When these two very rare conditions, an excessive fall and considerably elevated ground, are wanting, Guglielmini lays it down as a general rule, in the ninth chapter, that no river carrying gravels should at any time be made to enter another river of which the bed shows only sands or slime; that the line of such tributaries as bear gravels pretty nearly to their mouths ought never to be shortened; and that, on the contrary, it is more advantageous to carry the opening of the affluent lower down, and to prolong its course by windings, so as that room may be afforded for its depositing all its gravels before it is introduced into the other river. This great master on river subjects has also informed us, that the great Po itself, although abounding in water, had never occupied a fixed bed, till, after having ceased to flow over a gravelly bottom, it no longer received from any of its tributaries any other matters than sands.

All that was said, at the beginning, on the nature of gravels and sands, forms an unanswerable and a decisive objection against this project, as well as against that described towards the end of the first Book. The Reno and the four other torrents convey at present a considerable quantity of gravels beyond the track of the Upper Line. The quantity of gravel that would accumulate in the proposed new bed would be still greater, because the streams of the affluents, falling into it from sluices of ten or fifteen feet, and even more, must be greatly accelerated both above and below their entrances, and consequently tear up from their bottoms a great quantity of substances. The abundance of the gravels would be further augmented, if the sluices placed at the mouths of the tributaries might finally expand upon that of the receiver; to say nothing of the case in which some sluice might be blown up in the time of a high flood, and consequently carry desolation through the country. In this state of things there would be no room to hope, that the impetuosity of the floods would merely reverse the bottom of the whole river, in excavating it to a considerable depth; and that, in such an inversion, the weightiest matters must settle in the lowest parts, leaving those above them, which, as being lighter, might be easily carried away by the stream. This might sometimes happen, if the bottoms were composed of detached moveable substances; and it is in this view that Viviani has observed, that the largest masses of gravels, when attacked with great impetuosity by the current, in floods, are subject to very considerable changes, passing from right to left, and from the surface to the bottom. But the bottom of the new river, being composed of fresh and tena-

cious earth, can never be perceptibly subverted by the impetuosity of the waters, which, in high floods, will flow over it in parallel directions. Therefore, as there is no longer any reason to expect that, either by means of their collision or reciprocal friction, the gravels will be finally dissolved, or even sensibly diminished in number or in size, they will remain heaped up, on the new bottom, in proportion as they are brought down by the tributaries, and will continually raise it, to the great obstruction of the drains of the country, and to the constantly increasing risk of the embankments.

In fine, there would not remain even the hope, that by means of a great fall, the coarse sands, which would be thrown into the new bed by the tributaries, might be more readily triturated and detached from the bottom. One may venture to assert, on the contrary, and in general as far as regards the fall, that although the Upper Line commences from a more elevated point, it would, nevertheless, possess no sort of advantage over the Lower Line of the Primaro. The bottom of the Reno, at Malacappa, is certainly 59 feet 2 inches above the common horizontal of the last-taken levels, and, at the breach Panfilia, 37 feet 7 inches 7 lines; and hence it has been concluded, though very erroneously, that the gain in the fall would be, by the Upper Line, above 21 feet.

In the first place, it ought to be observed, that the bottom of the Samoggia, at the distance of two miles and a half from the Reno, at the spot where it would be necessary to turn its present course, is higher than this same horizontal by 60 feet 8 lines. Now, as the reduced declivity of the Samoggia, from the entrance of the Lavino to its present opening into the Reno, is

about 3 feet per mile, it would require a total fall of 7½ feet to reach the Reno at Malacappa; consequently the new bottom, at this place, would not be more than 52 feet 6 inches 8 lines above the horizontal; and all the advantage in point of fall would be reduced to about 15 feet.

It is to be observed, in the second place, that the slope of the Reno, from Malcappa to Buono-Convento, is at the rate of 43½ inches per mile; that, in the higher space from Malacappa to Trebbo, the reduced slope is at the rate of 28⅓ inches; and that, in the lower space, as far as to the entrance of the Samoggia, the slope is 25 inches, which is afterwards lessened by 2/7 below the mouth, and decreases at last to 14¾ inches near the breaches. The mouth of the Samoggia is almost as far distant from Malacappa as the mouth of the Savena would be in the new line; therefore, if the Samoggia were made to enter the Reno at Malacappa, and by this union the fall of the Reno were lessened 2/7, there would remain either 31 inches, or full 20, according as the one or the other of these two preceding falls was adopted; and, if a medium were taken, there would not be much less than 24 inches per mile. On the other hand, the Reno having 18 inches below the present mouth of the Samoggia, one cannot doubt but that the fall ought to be greater below the opening proposed for the Samoggia at Malacappa, where this river would bring down its coarser sands, and where the Reno would not have entirely abandoned its gravels. Thus, in the Upper Line, the derivation would in truth commence from a more elevated point, but one at which the waters would require a fall very considerably greater than at the breach Panfilia.

M. James Mariscotti, the celebrated professor of mathematics, and superintendent of the waters of the Bolognese, having very well explained, in several of his learned writings, the insufficiency of the fall, the lengthening of the line, and the other inconveniences that must be encountered in this thorny project, we will only add that which results from the preceding principles. According to what has been said, the 24 inches fall of the Samoggia and the Reno at Malacappa might be reduced to 20 inches after the confluence of the Savena, and to 17 inches after the junction of the Idice, on the supposition that their floods arrived simultaneously, and that allowance were made for the different quality of the substances which they carry down. But the Idice, the Centonara, and the Quaderna, would carry into the new bed gravels and sands much coarser than those which would be brought by the Reno and the Savena; consequently, the fall of 17 inches, which the advocates for the Upper Line have proposed to give to the new bed below the Centonara, would no longer suffice. In following the same track, it might be proved, that, in commencing the derivation of the Reno about Sampieri, and going on straight to Saint-Albert, 12 inches would not be sufficiently below the mouth of the Idice, whilst it may be believed that this very fall is more than is required below the present opening into the Benedictine Canal. So that, generally speaking, it may with truth be asserted, in regard to any upper line whatsoever, that, if the new bed is to begin in places more elevated than the breach at Panfilia, and the depression that must be made to receive the Samoggia, the greater slope that must be given to the higher parts of the Reno, and the coarser substances that the in-

ferior torrents would throw into the new common bed, are taken into consideration, there will be a great deficiency in the total slope, at the same time that, as the bottom of the Reno is already established on a smaller declivity at the Panfilia breach, and the other torrents bring down only substances successively finer in the lower trunks, the falls above assigned would be greater than the Reno would require, in flowing from this breach with the united waters to the Benedictine Canal, thence to Bastia, and at last to the sea.

CHAPTER III.

ON THE RESISTANCES OPPOSED TO RIVERS.

THE variety in the composition and texture of our globe everywhere presents to our view a great diversity of substances. Those which are generally found on the banks and bottoms of rivers, are gravels, sands, common earth, and clay. As the gravels are round, and the sands are furnished with points and edges, they cannot, from their conformation, lie so close on each other as not to leave free passages between them, through which fluids may penetrate. For this reason, cities which are built on the alluvions of rivers, as are Paris and Florence, sometimes experience, in places under ground, a considerable regurgitation of the waters, when the rivers begin to swell. Common earth is generally very loose, and has passages through it so open that the waters insinuate themselves, and penetrate the whole mass: besides, it often affords shelter to moles and rats and other creatures, which, by their winding paths, render the corrosions easier. Hence it is, that embankments made of earth are not very substantial, unless they are faced with clay, as is the custom in many places; and especially in Holland, where the bituminous earth is more porous than ours. Clay is a denser earth, which does not afford a free passage to particles of water through its very small openings, and which, in time, dries and

hardens: it is of this material that the strong dikes of the Meuse, the Rhine, and the other rivers in Holland, are formed. The Meuse, since, in its own bed, it is exposed to all the tempests of the sea, and its mouth is obstructed by different sandbanks, has, on the Delft side, a dike of clay 10¼ feet in height, which is higher by 4 feet than the level of the highest floods. The base of the embankment is 60 feet wide, and the breadth on the top 10 feet 5 inches, as laid down by M. Van Bleiswick, in his excellent treatise on dikes.

Pure earth exhibits to our view a great variety of appearances, and a long graduation of layers, from those which have more consistency, to those masses of more detached particles, which, being softened sometime by subterranean waters, or those of the rains, run down into the sinuosities of the mountains, and form what are vulgarly called *lavines.* The great quantity of these *lavines* found on the faces of the mountains between which flow the Panaro and the Reno, supplies in a great measure their common turbids, and renders the high roads in these parts very insecure. I have observed *lavines* of brown stone in the province of Frignano, which are more than 4000 feet in breadth, and which are constantly in motion; and I have seen the great *lavine* of Castello, which commences at Mount Cimon, and extends with incessant undulations to the banks of the river, and which, a few years ago, even carried away a mill, and shook several houses. This obstacle, and several other particular reasons arising from the very nature of the place, induced me to think, that it was not proper that the new road, which they wished to make from Pistoia to Modena, through the province of Frignano, should run for any distance along the bank of the Panaro; and as,

among the adjoining mountains, that of Boscolongo offered a commodious passage of the Apennines from the valley of the torrent Lima to that of the Panaro, and from Cutigliano to Fiomalbo, I proposed that the new road should cross the three principal branches which form the Panaro, and ascend the mountain on the other side of the valley, until it joined the other road made a few years before, by which, with some corrections, a very convenient road might be continued as far as Modena; and this is precisely what has since been carried into effect with great success.

In various parts of Holland, but chiefly in the vicinity of the lake of Haarlem, I have observed another species of earth, so rotten and so loose, that it is thrown down, with the greatest ease, by the impetuosity of the winds and waters, whence the lake gains continually on the land. Before the year 1531, there were four distinct and separate lakes, forming altogether about one-third of the extent of the present lake: a furious tempest so completely broke up the bottom, that the four lakes were thrown into one. In 1591, by an inundation, the quantity of the water was nearly doubled, and it has still been gradually increasing to the present times. The necessity there is to dig for turf or bitumen, which serves in Holland for fuel, and of continuing these excavations in the neighbourhood of the lake to the depth of even 40 feet, gives cause to apprehend that the waters may still further extend themselves in future. Of late years precaution has been taken to surround the lake with large dikes, particularly on the Amsterdam side, the most critical and dangerous part.* The levels of the other

* The Great Lake, or Haarlem Mere, has latterly been most successfully drained, and the land so reclaimed cultivated.

waters in its vicinity will not suffer the extent of the lake to be restrained in any other manner. As our marshes are formed by other causes, other remedies may there be applied. For example, the Pontine Marshes might be drained by forming a fixed bed for the torrents which enter and spread over them, so as to convey and discharge them into the sea by the shortest route. The marshes on the higher parts of the Adige might be greatly limited, and that in a short time, if the waters, which have not a sufficiently direct declivity towards the river, were drawn off in canals parallel to it, and so conducted into the river at some lower point.

I have also observed, in the valleys of the Bolognese, another kind of shaking and moveable ground, which forms in the middle of the waters, appearing like so many floating islands, and commonly called *cores.* Geminiano Montanari has well described their origin, in his discourse on the Adriatic Sea. Sometimes the reeds of the marshes produce, at the spot where they grow, an abundance of roots, which at the end of some years, become so thick and interwoven, that, as the little fibres, by which they are fastened to the bottom, begin to decay, the whole mass of earth which they contain having become specifically lighter than the water, is detached from the bottom, rises in large portions, and floats on the surface; which, however, does not prevent the *cores* from producing new reeds, as if they were still occupying their former place at the bottom; because the substance of the old roots contained in the floating masses supplies them with sufficient nourishment. In this manner they continue, for several years, to produce fresh herbage, and sometimes they grow so large as to bear cattle, sportsmen,

and cottages, and are the admiration of all those who come to see them. I have, in the valley of Duiglio, been upon one of these *cores*, which was upwards of half a mile in circumference: its thickness was about three or four feet, and below these there was a depth of more than twenty feet of water. When the sands and earth brought down by the tributaries either fill up the whole space between the bottom and the *cores*, or make them specifically heavier than the water, and sink them to the bottom, they are no longer anything but an elastic and compressible body, placed on a firm base, yielding at first uniformly, but, in the end, when compressed by the weight of an embankment, incapable of causing any derangement. Thus, the large *cores* met with in the valley of Gandazolo formed an insurmountable obstacle when the Benedictine Canal was first undertaken; but those that are found consolidated and sunk in the earth, at a place called the Traghetto, towards the confluence of the Idice, have not in any way obstructed the progress of the works: and already, for some years past, the deposits left by the Idice in the valley of Gandazolo have so well consolidated the *cores*, that there is no longer any difficulty in continuing the embankment in a straight line.

But these phenomena are very rare, and such as Nature exhibits only in certain places. The unequal resistance and cohesion of substances which are generally met with in rivers, the different mixtures of earths, and sands, and gravels, the variety and irregularity of their distribution, render the beds of rivers at all times liable to unequal corrosion, forming here and there little sinuosities, which occasionally become very large, and force the rivers out of their first direction, and that chiefly when their bottoms are composed of

gravels: for the gravels, which are floated down in the time of floods, are not always equally distributed over the whole bed: on the contrary, they are sometimes accumulated in such large quantities on one side, that they drive the thread of the stream to the other. It is from this cause that rivers experience, in their higher parts, where they carry gravels, more frequent alterations in the direction of their stream, oftener change their beds, and are constantly more irregular, and more tortuous, than in the lower parts, where they carry only sands and earths.

Setting aside, however, the substances that are brought down by rivers, the simple difference of those which are found on their shores, and on their bottoms, always gives occasion to different corrosions, and is sufficient, even when a river is enclosed between two parallel banks, speedily to compel it to change its course. Whenever, therefore, the making of new beds is in question, even in the case of such rivers as float down the lightest substances, there should always be left, along the whole bed, broad shelving brims, and open low shores, whilst the mounds are kept at a due distance from the excavations, that the waters, having free space to operate, may form their corrosions, and twist and adjust their bed at pleasure, without directly attacking the embankments.

Guglielmini has treated this subject at great length in his sixth chapter on the Nature of Rivers. The foundation of his whole argument is, that if a stream, even when enclosed between parallel banks, begins to make erosions on any part, whether because the ground has there less tenacity and consistence, or the force of the water is there increased by the repercussions of the parts above, it will be the points and angles of the

places corroded that will be first overthrown, because those parts present the least resistance, and there the force and impetuosity of the current are the greatest. Thus the whole erosion will in a short time become one continued curve, and the thread of the stream, flying off from this side, will go and batter the opposite shore; and so, in the constant renewal of the same play, when an erosion has been made on the right bank of a river, another will be made on the left, and then another lower down on the right, till in this manner the whole river will become a continuation of arcs alternately concave and convex; and, as the strength of the stream progressively lessens in proportion as the angle of the current with the corroded shore becomes more acute, the obliquity of the thread of the stream, impelled and repelled, becoming greater as the concavity of each erosion is enlarged, it will so happen that the force will at last become equal to the resistance, and each erosion will have its limit, which might be ascertained, if the laws of the force of the water, and of the resistance of the ground, were known. But it may in general be asserted, that a sandy shore will yield more easily than one of loam; that the erosions will be so much the greater, as the current of the river shall strike the shore more directly; that the broader the river, the farther will the erosions penetrate; and that, all other circumstances being equal, the larger the rivers, the more considerable will be the circuit of their windings.

Hence it is, that in some places, when erosions take place, they are accustomed to throw back the embankments, and to wait until the erosion has reached its limit. In other places, the high perpendicular corroded bank is sloped off so as to present an inclined

plane to the stream, wherever it attempts to undermine it: but this is attended with a waste of ground, not always admissible; and, in most cases, the encroachments must be promptly checked, and their progress effectually prevented. Various defences, on a large and a small scale, have been invented for this purpose, and are used in great and small rivers. In several parts of the Arno, and of the Secchio, large stones, scattered in great quantities along the corroded shores, produce good effects; because, even when they are carried down by the impetuosity of the current, the different intermixtures, which they form among themselves, produce a continued and multiplied resistance. I have seen, in several parts of the lower bed of the Primaro, a single row of piles sufficiently secure the dikes of the valley of Commacchio. In the higher parts of the Reno, I have seen larger and stronger piles driven in obliquely, so as to form a slope down to the bottom of the river. In the journeys which I have had occasion to make along the Po, and other rivers, I have examined different sorts of spurs, and have found but few of them that were not shaken and damaged by the current, and by gulfs, which are readily formed at the inner and outer extremities of these works. The five spurs, which have stopped the erosion at Parpanese on the Po, in a very elevated steep shore, form an obtuse angle with the upper bank, to which they are strongly secured. They commence with a base of about twelve gabions, made of willow twigs, and filled with earth, which sustain between their angles eleven gabions, upon which are placed ten more, and so on, the number in each course lessening gradually to the top, where there are only four or five.

Famiano Michelini, in his "Treatise on the Direction of Rivers," is the first author who has written on the defences that might be opposed to waters; although he has not formed a correct idea of the pressure, which, even in standing waters, arises simply from the depth. Barratieri, in treating of spurs, has laid down no rules on the mode of placing them: he merely takes it for granted that they ought to be fixed where the corrosion is the deepest; whereas, on the contrary, it is easy to see, that one ought to begin to turn off the current at the very edge of the erosion, and that the spurs fixed lower down should be so placed, and at such proportional distances, that they might mutually support, and be supported by, each other. Guglielmini and Zendrini have treated this subject in a superior manner. By following up their common principles, the most advantageous position that can be given to a spur, for turning the current of a river towards the opposite side, may easily be determined. For, supposing, in the first place, that the direction of the water is parallel to the banks, and resolving, by the common rules of Mechanics, its velocity into two others, the one perpendicular, and the other parallel, to the spur; the latter velocity will be proportional to the cosine of the angle which the spur forms with the under bank. Then, further, as the quantity of water that impinges against the spur is proportional to the perpendicular drawn from the point or outer extremity of the work to the bank, or to the sine of the same angle of inclination, the quantity of motion with which the stream will flow, in a direction parallel with the spur, towards the opposite shore, will be as the product of the sine into the cosine of the angle which the work makes with the bank:

and since this product is a maximum, when the angle is half a right angle, it clearly follows, according to the principles above quoted, that the most advantageous position which can be given to a spur, or buttress, is that in which it forms with the under bank an angle of 45°.

However, if it were thought necessary to construct a spur, I would recommend, in the first place, that it should be well fixed in the shore: next, that it should make, with the under bank, half a right angle; and, lastly, that from the head it should slope towards the extreme point, and run out on its two flanks, to meet the bottom of the river obliquely, both above and below. But, even by these means, one can never prevent the water, impetuously striking against the angles and projecting points, and beaten about in various directions, from forming deep excavations, which by degrees will weaken, and at length overset, the work. I have seen great whirlpools in the Danube, and in the Adige, and in other rivers, at those spots where the bulwarks and the shores were struck most forcibly in front. I have uniformly discovered gulfs and eddies in the vicinity of the best constructed spurs. A rampart of fascines, or of stones, extending the whole length, and descending with a regular slope, so as to form a very acute angle with the bottom, would be free from this inconvenience. I should therefore prefer the uniform distribution, over the whole of the corroded bank, of that resistance which is usually made, at intervals, by spurs. In Holland, I have seen no other sort of bulwarks than strong dikes, and extensive works of fascines, which have produced the most excellent effects. The greatest fascine work is that which is opposed to the impetu-

osity of the Meuse under the walls of Rotterdam. The largest dikes are towards the North Sea: they have, on the ground, a broad and thick layer of bricks and rubbish, which is covered by large stones, of which the vacuities are filled up with lime, and smaller stones; and their slope is so gradual, that, in some places, the height is to the base as 1 to 13. Within the present century, also, other great dikes have been constructed in Zealand on the coast of the ocean, in those places where the large heaps of sands, which extend the whole length of the southern shore, and which are commonly called *Downs*, are interrupted. These dikes have about three perches of altitude on a base of thirty-five.

CHAPTER IV.

ON THE REGURGITATION OR BACKWATER OF RIVERS.

FATHER GRANDI, in the fourth chapter of his Second Book, having explained the method of finding the equivalent origin of a river, and of making the correction for that which is subducted, by the various resistances, from the velocity of the whole fall, has considered, among these resistances, principally, the regurgitations occasioned by the floods of the tributary streams, the reeds and shrubs which grow sometimes on the bottom, the angles and least regular turnings of the banks; and he shows that he makes very little account of the other resistances, which are produced by the roughness and inequalities of the edges and bottom. He remarks, that the resistance of the banks terminates in those parts which slide near them, without extending to the other parts in the middle; and, conceiving a line to be drawn along the summits of the highest parts of the bottom, he is of opinion, that the waters above that line cannot experience any impediment from the other waters, which lie dormant below it in the hollows formed by the heights: and, finally, conceiving another straight line to be drawn from the surface of the tributary, and continued horizontally, above its entrance, until it meets the bottom of the receiving river, he has determined the limits of the regurgitation caused in one river from its junction

with another, by demonstrating that, over all the space beneath this line, the waters of the tributary would regurgitate and obstruct it, whilst in the whole of the space above it the waters would remain equally as free as if there had been no affluent or tributary.

The demonstration of Father Grandi applies very well to the case of a wear or similar obstacle traversing the bed of a river, on the hypothesis that water is perfectly fluid, and composed of particles entirely detached from each other. On the same hypothesis, it would appear that the extent and the quantity of the regurgitation ought to be less in the case, not of a fixed obstacle, but of two rivers flowing to unite, and both contributing in the common bed to urge on the waters. However, in the one case, as well as in the other, the space covered by the reflux ought to be greater, as the particles of water are united together by a certain adhesion, which prevents their separating without some difficulty: this is what is commonly called the adhesiveness of water. We have this adhesion before our eyes, in the concavity formed by the surface of the water in vessels that are not full, and in the roundness or convexity which it assumes in vessels that are very full, before the upper waters are detached from the lower, and begin to run over the edges. The foam, the ebullition, and the tenuity to which the surface of the water is reduced before it is broken by the little bubbles of air escaping, the experiment of the hydrometrical flask mentioned in the preceding book, and many other similar phenomena, are clear proofs of this truth. The adhesiveness of the water must cause the obstructions, whether they arise from the regurgitation, from the shrubs and roots that are at the bottom, or from the roughness and inequality of the bottom and banks, to extend to

greater distances than those which have been assigned by Father Grandi.

In the first place, supposing a river to be traversed from one side to the other by a wear, from whose summit a horizontal line has been drawn, the waters will be stagnant in the whole of the angle which is formed by the wear with the upper bed; and since, as soon as a river is once reduced to a permanent state, there must pass through each section an equal quantity of water, the sections that are cut by this horizontal line, and are partially obstructed, must increase in height in proportion to the extent of the part obstructed. By this means, the surface of the river will there have less slope than it had before, and the slope will gradually lessen as one goes upwards, till one reaches the section which is placed completely above the horizontal line. On the contrary, at the summit of the wear, the waters precipitating themselves freely will there lower their height, and their surface will have a greater slope; and as the greater slope of the surface, independently of other circumstances, has an influence on the greater acceleration of the waters according to what has been laid down in the second chapter of the Second Book, the waters will begin to be accelerated, even before they reach the top of the wear. The adhesion or tenacity of the particles must therefore cause the acceleration to extend upwards to a distance greater than it would do on the hypothesis that the same particles were perfectly detached from each other; for the particles, which are accelerated by the greater slope of the surface, and by the free fall which they have of the whole height of the wear, must draw after them those which immediately follow them, and these, others in their turn; and so on, successively, for

some distance. This is precisely what has been asserted by all authors, and chiefly by Guglielmini in his seventh chapter, and Manfredi in his Annotations.

I think it right to add to these theories an observation that is important. As the particles of the waters begin to be accelerated before they reach the summit of the wear, from the increased slope of the surface, so the diminished slope of the same surface, throughout the whole space regurgitated, must make the waters swell farther back than they would do simply on account of their stagnation. Thus, the tenacity and adhesion of the particles, by means of which the acceleration extends itself to a greater distance above the top of the wear, must occasion the regurgitated waters to retard others, and their retardation to be in some degree communicated to those sections which are entirely above the horizontal line drawn from the top of the wear. But as the space within which the waters begin to be accelerated, before they reach the wear, is perceptible, so also the stagnation of the waters ought to extend to some sensible distance above the horizontal line, which would be the limit of the regurgitation, on the hypothesis of the perfect fluidity of the water, and of the equality of the slope of the surface. The lowering of the sections begins to be sensible at a great distance above the sluices in great rivers: and in little mill-races, that acceleration which can be distinguished by the eye, or by means of floating bodies, begins at the distance of eight or ten feet, and more, from the sluices, as I have frequently ascertained by experiment. In all canals, then, large or small, the regurgitation will always extend a sensible space above the horizontal line drawn from the summit of sluices, or of any other fixed obstacles.

In the particular case of mill-races, there is another reason why the regurgitation should begin to be discernible still higher up than could be occasioned merely by the obstacles placed below, or by the adhesion of the particles of the water. Let us suppose several works placed in succession on the same canal, and then observe what will happen: the water falling from the first detention upon a wheel, and striking right against the bottom of the canal, ought instantly to lose the vertical velocity which it had acquired in its descent, and to adjust its motions according to what is suitable to the body of water, and to the declivity of the bottom, and of the surface. It is in this manner that, in the cascades even of large rivers, we see that the stream reduces its rapidity very speedily to the velocity that suits the state of the beds in which it is to continue to flow. The freer the bottom of the canal, and the greater its slope, the more readily will the waters falling under the wheel run off, and continue their course: by which means, on the one hand, the resistance to the boards of the wheel will be less, and, on the other, the force and impetuosity of the water will be greater. On the contrary, if a dam has been placed lower down for some other work, and if the horizontal line, drawn from the summit of this other dam, meets the bottom a little below the first wheel, the water will no longer flow off so plentifully, and it will there rise to a greater height: whence, on the one hand, the revolutions of the wheel will be performed with greater difficulty, whilst, on the other, the moving force and impulse will be less.

From what has been said, it follows, that the case of canals, which serve to set wheels that are placed

successively one behind another in motion, is not properly that of a body of water which flows down a continued bed, until it meets with a wear, or some immovable obstacle. It is, properly speaking, the case of a stream issuing from a reservoir by an inclined canal, the inclined canal serving to give an off-run to the water, which would remain stagnant under the wheel, in proportion as its course downwards might be less free. In this case, the regurgitation occasioned by an obstacle placed farther down may very easily extend itself to the wheel and the upper work, even when the horizontal line, drawn from the summit of the obstacle, would not reach them; since the motion of the water is stopped, throughout the whole space which is below the horizontal line, in consequence of the obstruction produced by the obstacle, and the tenacity and adhesion of the particles of the water must cause this obstruction to extend itself still farther up the canal, to a sensible distance. The course of the water passing under the wheel will therefore be less free, and consequently its resistance and height will be greater: and, on the contrary, the force of the water which is constantly coming down will be less; which, however, would not happen if the horizontal line, drawn from the lower impediment, met the bottom of the canal at such a distance from the upper wheel, that it could not cause any sensible alteration in the upper waters.

The controversies which originated at Roveredo afforded me an opportunity of verifying all these principles by the most accurate and conclusive experiments. The foot of Roveredo is to the Parisian foot very nearly as 12 to 11. The summit of the sluice of the lower mill was found to be $2\frac{3}{4}$ inches lower than the horizontal line drawn from the bottom of the

canal at the point where the wheel of the upper mill was placed: the horizontal line, drawn from the summit of the same sluice of the lower mill, struck the bottom of the canal at the distance of $84\frac{1}{2}$ Roveredo feet from the upper mill. Towards ascertaining whether the limit of the regurgitation was truly that of the horizontal line drawn from the top of the obstacle, I first of all caused the height of the lower sluice to be raised $1\frac{1}{3}$ of an inch, so that its summit was only $1\frac{5}{12}$ of an inch lower than the bottom of the upper canal: having then adjusted all the waterfalls, and taken every possible precaution to prevent any variation in the body of water during the experiments, I measured its height on a little pilaster, placed at the distance of 55 feet from the upper mill, and $29\frac{1}{2}$ feet from the place where the horizontal line, drawn from the summit of the lower sluice, struck the bottom. I likewise observed the time required that the wheel of the upper mill might make 40 revolutions, under the different circumstances of leaving the lower sluice of its usual height, or of raising it one inch and a third, and of letting the stream fall freely, or of causing it to strike, in falling, on the wheel. Farther, I marked on the same little pilaster the time of 40 revolutions, and the height of the body of water in the two different cases, in which the lower sluice was left at its common height, or was lowered $2\frac{7}{8}$ inches, all other circumstances remaining equal, and the same precautions being again taken, that in both cases the same quantity of water should be supplied to the canal. Lastly, I repeated the double set of experiments in different states of the water, as supplied to the upper wheel in the greatest quantity possible, or in a medium quantity, or in the least. The following were the results:—

Table of Experiments.

	Time required for Forty Revolutions.		Height of the Water.
	Minutes.	Seconds.	Inches.
First Experiment.			
When to the ordinary height of the sluice an obstruction of one inch and one third had been superadded, the lower wheel being in motion .	22	30	17
The sluice left of its common height, the wheel in motion . . .	21	0	$16\frac{9}{16}$
Sluice as in the last, but the wheel stopped	20	20	$16\frac{1}{2}$
Second Experiment.			
In another state of the water, with an obstruction of one inch and one third, the lower wheel being in motion .	20	0	$16\frac{5}{16}$
With an obstruction of only one inch, the wheel in motion . . .	20	0	$16\frac{3}{16}$
With the ordinary sluice only, the wheel in motion	18	45	16
Third Experiment.			
With the smallest quantity of water, an obstruction of one inch, and the lower wheel in motion . . .	21	30	$11\frac{5}{16}$
Without the obstruction, the wheel in motion	20	45	$11\frac{1}{16}$
The same, only the wheel stopped .	20	30	$11\frac{1}{16}$
Fourth Experiment.			
In another state of low water, with an obstruction of one inch and one third .	19	8	$11\frac{1}{2}$
Without the obstruction, the wheel in motion	18	30	$11\frac{11}{16}$
Fifth Experiment.			
With full flood and the common sluice, the lower wheel turning . .	20	18	$15\frac{5}{8}$
The sluice lowered two inches and seven eighths, the wheel stopped . .	18	52	15

Table of Experiments—continued.

	Time required for Forty Revolutions.		Height of the Water.
SIXTH EXPERIMENT.	Minutes.	Seconds.	Inches.
In another state of high water, the sluice of its common height, the wheel in motion	18	27	$15\frac{3}{4}$
The sluice lowered as in the last, the wheel stopped	16	59	15
SEVENTH EXPERIMENT.			
In another state, sluice of the ordinary height, wheel in motion . .	23	38	$15\frac{1}{2}$
The sluice lowered and the wheel stopped	21	38	15
EIGHTH EXPERIMENT.			
The water in a medium state, the sluice of its ordinary height, and the wheel in motion	21	8	$12\frac{1}{4}$
The sluice lowered and the wheel stopped	20	4	$11\frac{3}{4}$
NINTH EXPERIMENT.			
The water low, the sluice of the ordinary height, the wheel in motion . .	20	45	11
The sluice lowered and the wheel stopped	20	8	$10\frac{3}{4}$
TENTH EXPERIMENT.			
In another state of low water, with the sluice of the ordinary height, and the wheel stopped	20	2	$10\frac{3}{4}$
The sluice lowered and the wheel stopped	19	49	$10\frac{5}{8}$

The sixth experiment was carried on under the same circumstances as the fifth, only the fall which supplied the stream to the mill-race was a little raised; and in the seventh experiment, it was a little lowered.

The result of all these experiments is, that although the obstacle placed below did not reach the horizontal line drawn from the bottom of the canal under the

upper wheel, yet it always increased the height of the water there, and diminished its velocity; and that the resistance, arising from the obstruction made by the lower wheel to the free discharge of the water, occasioned of itself a sensible retardment to the motion of the upper wheel. All the differences, either in the height of the body of water, or in the number of the revolutions made in a given time, became smaller as the body of water was diminished; and that, not only because this very difference in the height of the sluice occasions a less variation in the slope of the surface when the waters are very low, but also because, when the waters are superabundant, the disburdening channels, re-entering the principal canal below the first wheel, raise, with the water which they carry, the surface of the other water, which has already fallen underneath the wheel, and by this means increase the resistance, and diminish the impetuosity and the moving power. The differences of the heights in the fifth, the eighth, and ninth comparative experiments were, five-eighths, one-half, and one-quarter of an inch, that is, in the proportion of the numbers 5, 4, and 2. The difference in the time of the forty revolutions was, in the fifth experiment, one minute twenty-six seconds above eighteen minutes fifty-two seconds; that is to say, more than seven hundredth parts: it was five hundredth parts in the eighth experiment, and less than three hundredth parts in the ninth. Some other comparative experiments were tried, when the waters were unusually low, since, at the pilaster, there were only eight or ten inches of water; but no sensible difference was observed, either in the height itself or in the time.

CHAPTER V.

ON THE ENTRANCE OF RIVERS INTO THE SEA.

THE Mediterranean, and particularly the Adriatic, offer to our consideration two very curious and highly interesting phenomena—the prolongation of the shores in various places, and the uniform heightening of the surface of the sea. One might, upon a single principle, assign a cause for these two phenomena, by stating, that the substances brought down by the rivers and collected on the beach, throw forward the shores; and thus, by contracting the outline, must necessarily elevate the surface of the sea. This explanation would appear very plausible, if the Baltic did not exhibit, at one and the same time, an enlargement of its shores and a depression of its superficial level; and, if it were not evident that, as all the seas must be upon a common level with respect to each other, the absolute height of the waters cannot be raised in one, without being at the same time elevated in all the rest. But, to confine ourselves exclusively to facts:—in the memoirs of the Royal Academy of Stockholm, MM. Celsius, Dalin, Stembeck, and several others, have given a long statement of facts, which prove very clearly the extension of all the shores. They state, among other facts, that the fisheries have failed in several places, because the water is become too shallow; that several creeks and harbours in the Gulf

of Bothnia, once capable of sheltering large ships, can now admit only small vessels; that, in our own time, several islands have been united to the continent; and that even the whole continent of Sweden was formerly only a cluster of islands.

The prolongation of the shores might still further agree with the elevation of the level of the sea, wherever particular causes contributed more to the increase of the beach, than general causes to the elevation of the bottom, and of the surface of the sea. But the observations made in Sweden exhibit also a diminution of the absolute height of the sea. We there perceive, that several spots, where, formerly, dog-fish were caught, are at present, from their elevation, entirely out of use as fisheries; that several shelves, where ships were formerly wrecked, may now be easily distinguished; and, above all, that the signals and marks, which were placed formerly to show the height of the surface of the sea, are at present considerably above that surface.

The continual rising of the level of the waters in the Adriatic was not unknown to the learned of the sixteenth century; and the engineer Sabbadini has formally stated the opinion in his Discourse on the Lake of Venice. Eustace Manfredi was the first person who established the fact. When he was at Ravenna, he perceived, in taking some levels, that the floors of several ancient edifices in that city were below the level of the sea. The principal of these edifices were the Cathedral, the Rotunda, and the magnificent Church of St Vital, which was erected in the reign of Amalasonte, and which I found it impossible to behold without entertaining a great esteem for the architects of those days. Now, as the sea formerly

reached Ravenna, and it is not to be supposed that such able architects would build in places likely to be inundated, one is forced to conclude, that in their time the surface of the sea was lower. Bernardin Zendrini has confirmed this opinion by other observations of the same nature, which he made at Venice; where he observed, that the rings formerly used to fasten boats are now below the level of the sea; that the subterranean Church of St. Mark is no longer serviceable, because it is below the water; and that the ground-plot of the Piazza is sometimes overflowed in moderately high tides, although, some time since, it was raised about a foot. The same remarks have been made in regard to the Mediterranean. In the Isle of Capri, the whole platform of an ancient Roman edifice, placed on the seashore, is at present inundated: and at Viareggio, and in several other places, many pavements are in like manner under water. But to silence all objections, which might be started by alleging that such changes might arise from the accidental sinking of the whole ground, it is sufficient to produce the observations made by the celebrated Vitaliano Donati all along the coast of Dalmatia. At Lissa, at Diolo, at Zara, and at other places, the level of the sea is higher than the floors of several very ancient buildings, which, we must suppose, were originally constructed above this level, that they might be healthy, and be provided with convenient drains: yet as these edifices are erected upon the solid rock, of which this shore is entirely composed, it is not possible even to suspect that the buildings have sunk in any one point.

The prolongation of the shores is clearly shown in several parts of Italy also, but principally in Tuscany, Romagna, and La Marca. The ancient port of Pisa

is at present very far distant from the sea; and this is likewise the fate of several towers built long ago for the defence of these coasts. The city of Ravenna, formerly situated on the Adriatic, is at present inland.* It is also a fact, that the whole shore of the Po, as far as Ancona, is extending itself sensibly every year. Zendrini, in the fourth chapter of his Report on the Diversion of the Ronco and the Montone, has inferred from ten observations, that this extension went on at the rate of about 23 perches annually. He has moreover assigned for it two different physical reasons. In the first place, he has observed, that the shore is exposed obliquely to the south-east and the south winds, of which it is the property to scoop it out, to use a sea-phrase, in sweeping off the sands; and that it is exposed in front to the north-east and the east, which drive the sands on the shore, and accumulate them there. Now, as the sea, not only in tempests, but even in ordinary tides, raises the sands from the bottom, the consequence is, that as the direction of the winds concurs to transport them, and collect them on the beach, the shore is continually more and more extended, and thus the sea is thrown off to a greater distance. Then, as the largest sandbanks are found at the mouths of the rivers Savio, Ronco, Montone, &c., where they extend themselves in an irregular manner, chiefly towards the right, Zendrini has concluded that the extension of these banks should be attributed to the slow motion of the sea, and to the silt and sands brought down to the spot by the rivers. In fine, Zendrini, having visited all the ports of Romagna, to ascertain what measures could be taken

* Under the Roman emperors, it was celebrated for its capacious harbour; it is now above three miles from the sea.

to render them more secure, and having seen that the river sands were not, in any instance, carried along the coast for more than six or seven miles, determined, among other conditions, that a harbour ought not to have a turbid river, either to its right or to its left, within the distance of seven or eight miles.

The subject of the damage, which harbours on the seacoast are liable to sustain from the mud and sands of rivers, has been already discussed in a discourse on the Adriatic, by Geminiano Montanari, on occasion of the suspicions entertained by some, that the sediments of the Old Piave were carried, more than nine or ten Venetian miles, to the Port of St Nicholas. This illustrious philosopher maintained, that the transportation of these deposits could not arise from any other cause than the currents; that is, from the sweeping motion along the coast, with which the waters, that are constantly entering through the states of Gibraltar, on the Barbary shore, having run along the whole circumference of the Upper and Lower Seas, or, in other words, of the Adriatic and Mediterranean, return back to the ocean by the coast of Spain. Seafaring men were made sensible of this motion, in the sixteenth century, by the difference of the time which they took, when the winds and other circumstances were equally favourable, in going to and in returning from Corfu to Venice; and hence it became the practice to coast along the northern shores of the Gulf in going from Corfu to Venice, and to keep, on the return from Venice to Corfu, the southern shores, along the coast of the Ecclesiastical States, and the kingdom of Naples. They have since discovered, by the motion of floating bodies, the precise direction of this current, both in the Adriatic and in the Mediterranean. Montanari has deter-

mined, from the observations that were made on this motion, that the velocity of the current was only three or four miles in twenty-four hours ; whence it follows, that, as the rapidity of river-streams is about three or four miles an hour, the proportion of the two velocities must be as 1 : 24. Montanari has gone still further, and has decided, on the same principles, that it necessarily required three stipulations to be granted, that the sediments of the Old Piave might float as far as Port St Nicholas: namely, that these sediments should be three whole days on their way; that, during these three days, the state of the sea should be such as to prevent the sediments from subsiding to the bottom ; and that the tempests at sea and the floods in the river should both occur at the same time. But as these circumstances can hardly ever exist together, Montarani concludes, that the deposits have nothing to do with the formation of shoals in ports so far distant.

But there are still some other considerations, which deserve to be weighed on this particular fact. In combining the motion of the sea along the coast with the motion of any river at its mouth, it is evident,* that the waters of the river ought to take an intermediate direction, and turn their course more or less towards the right, as Guglielmini has remarked in the seventh Corollary to the fourth Proposition of his Seventh Book. Thus, the current and the river being both turned from their first direction, and the current being more so than the river, since the velocity of the river is about twenty-four times greater than that of the current, the sea, lying on the right hand, between the line in which all the blended waters are now directed and the

* Since the motion of the sea is, with respect to the rivers in question, from left to right.

shore, will no longer be assisted by the coast-current already broken and turned aside: the sediments incorporated with its waters will consequently begin to settle along that part of the shore, and form diverse sandbanks, which will go on gradually and continually increasing. And hence the river, finding always greater impediments on its right, will turn by degrees towards the spot where its course is more free, and, in time, will at last establish its course in a direction quite opposite to that in which it at first set out; that is, by tending constantly to the left of its opening. Montanari observes, that this is precisely the manner in which the mouths of the Tagliamento, the Piave, and other rivers in the Venetian States, maintain their outlets. Zendrini, in the Report before quoted, adds also the example of the rivers in Romagna; and, in the first chapter of another Report on the Harbour of Viareggio, he has applied the same principles to the rivers of the Mediterranean; with this difference only, that the tides being weaker in the Mediterranean, the motion along the shore is there more perceptible, and the deposits are formed to greater distances, and in much greater abundance on the right, while none are ever seen on the left.

Zendrini, passing afterwards from these general theories to some particular cases, and treating of the mode in which a harbour might be formed for the city of Ravenna, proposed that it should be opened at a spot where the Ronco and Montone formerly entered the sea, and from which the Lamone is a little less than eight miles distant. As at this distance nothing was to be apprehended from the sediments of the Lamone, or from those of the Primaro, Zendrini proposed, as a provision against all other inconve-

niences, that the ancient bed of the Ronco should be excavated to the breadth of thirty feet, and formed into a navigable canal, by uniting in it the clear waters of the mills with those of the drain of the city: and he persuaded himself, that in this manner he could collect a sufficient body of water to drive back and sweep away the sands brought by the winds and by the sea. Similar precautions are generally very effectual, and I could have wished that, at Pisa, they had profited by these instructions; and that, instead of raising the parapets of the banks of the Arno—to retain the floods, which are becoming higher and higher, as much from the excessive breadth and winding of the last trunk of the river, as from the numerous sandbanks that are found there—they had rectified and contracted the mouth of the river, by extending it into the sea by means of a double row of piles, according to what was proposed, towards the end of the last century, by the engineer Meyer, as we have before related.

The plans of Zendrini have not been strictly followed at Ravenna; and instead of the navigable canal which he recommended, they have formed an excavation in the very drain of the city, widening it, and prolonging it as far as the little ditch, and working in such a manner, that, by means of long rows of piles, the waters are kept encased from this reservoir to the mouth, which is not very far from the Lamone. In this situation, and with so small a body of water, it need not excite wonder that they have not been able to secure the harbour from the deposits of the Lamone and of the sea.

There are several measures which might be adopted to improve the present harbour of Ravenna; and the

principal one would be, to conduct the Lamone into the Primaro. But, although no change whatever were to be made, either in regard to the harbour or the Lamone, it is clear that, as the mouth of this harbour is more than seven miles distant from the Primaro, if all the waters of the Bolognese and of Low Romagna should be united, as has been before stated, all their sediments could not possibly do any mischief, either to the drains, to the harbour, or to the navigation of the city of Ravenna.

PLATE II
RIVER GOTHA below Trollhattan
Trollhattan
Sluice in ruins
REFERENCE
4 Small meadow land under water
5 Canal cut out in the rock
7 Great Outlet
8 Deep Valley
13 First Sluice
14 Ground laid under water
17 Ground defended against the River by an embankment
18 Two last Sluices
of the Adda
SECT
NB
A

AN ESSAY

ON

NAVIGABLE CANALS.

Navigable Canals are, to those people who inhabit inland countries, what marine science is to maritime nations; they are the resources by which Art provides against the greatest difficulties that the nature of the intermediate spaces, as well as the distances of remote situations, opposes to that reciprocal assistance which the wants of society and commerce require. The great navigations embrace the whole globe, and extend to all the principal objects of opulence and luxury; the smaller navigations serve to procure all the inferior and more common productions, at all seasons, and for men of every class of society. The former offer to our observation, on account of the difficulty of their execution, one of the greatest efforts of the human mind; the latter, not difficult in their execution, often require all the subtilty and industry of art in their construc-

tion. The most flourishing nations have always been engaged in enterprises of this kind, thus employing the studies and the leisure of peace.

II. The Chinese—that singular people, who were several centuries before us in the *invention* of printing, of gunpowder, and of the compass, and whom, nevertheless, we have left far behind in their *application* and their *use;* who have cultivated astronomy and painting without ever making any considerable progress in either; and who, with a wish to go into higher studies, occupy themselves, for the greater part of their lives, on a very complicated mechanism of reading and writing;—have in no instance so much merited the praises bestowed on them by travellers, as in that which relates to their dikes, their bridges, and their canals. Among all the water-works which contribute to the riches, and to the conveniences, of this extensive and populous empire, that which may rival the glory of European architecture is the Grand Canal, which joins the rivers Kiam and Hoambo, and which forms a continued navigation, for more than three hundred leagues, from Canton to Pekin. I presume that a geographical reader will readily find all the names of the intermediate places on the maps.

III. The first masters in science, the architects of the Obelisks, the ancient Egyptians, who, with such efforts of industry, compelled the waters of the Nile to fertilize their plains, and to form a communication between their cities, conceived a plan that might have changed the whole face of Europe, by shortening the distance between it and the East Indies and China. They began a canal, which was to establish a communication between the city of Memphis and the Arabian gulf, and so to continue the navigation of the

Nile and the Mediterranean. Strabo, Diodorus, and Herodotus clearly state the fact; and travellers still discover some vestiges of the work. The Caliphs roused the slumbering genius of the nation for astronomy, geography, and physics: they also undertook to form the junction of the two seas; but they did not carry on the works to any extent.

IV. The warlike and conquering spirit of the ancient Romans left them no leisure to engage in enterprises of this sort, in proportion to their knowledge and their greatness. The project of Julius Cæsar to excavate a canal from Rome to Terracina, the plan for the union of several rivers proposed in the reign of Nero, and others mentioned by Pliny as the ideas of Trajan, were never carried into effect. The canal by which Caius Marius supplied his camp from the Rhone, in the vicinity of Arles, was by no means an extensive work. We have no account of the date when the Peterborough canal, in England, was constructed. Lombardy was the only theatre on which the Romans chiefly distinguished themselves in undertakings of this description. Quintus Curius Hostilius made an opening into the Po from the Mincio, which joined the Tartaro and the ancient Philistine Canal. Æmilius Scaurus drained the marshes of Parma and Placentia by means of navigable canals. Augustus, by another canal, united the different branches of the Po with the ports of Adria and Ravenna.

V. Even in the darkest ages some monuments of similar works have been left. Odoacer has given his name to a canal which went straight to the sea from the river Montone before it reached Ravenna. The Moors opened a much larger canal from the city of Grenada to the river Guadiana, now called the Gua-

dalquivir. Charlemagne, in the vast extent of his expeditions, undertook the project of forming a junction of the Mayne and the Rhine with the Danube, and of the ocean with the Black Sea: he even began the canal that was to join the Almutz, one of the tributaries of the Danube, with the Rednitz, which discharges itself into the Mayne. The two canals, which form the communication of the Tesino with the Adda, and which unite at Milan, are the most perfect and most celebrated work of hydraulic architecture previous to the restoration of the arts and sciences.

VI. The Tesino, issuing from the Lake Verbano, now called the Lago Maggiore, after winding and dividing its stream into several branches in a great valley, and afterwards reuniting its waters into one bed, enters the Po near Pavia. The navigation is free throughout, although in some places very difficult, particularly at a precipitous pass, usually called del Pan Perduto. It is below this pass that they have derived the navigable canal from the Tesino, which extends to Milan, and which, at the Place di Abbiate, divides and forms another navigable canal, called di Bereguardo, that returns towards the Tesino. The whole length of the excavation is about thirty-two Italian miles: its breadth at the head, seventy Milanese cubits. But this breadth is gradually lessened in the lower parts, and is at last reduced to twenty-five cubits.

VII. The Adda, flowing out of Lake Lario, now called the Lake of Como, forms by the expansion of its waters, first, the Lake of Lecco, and afterwards the small Lake of Olginate; a little below which is a very steep fall, commonly called Ravia, the most dangerous passage, and the most difficult to navigate: as the declivity then fails, the waters are sustained

by a sluice of 125 cubits, which forms the little artificial lake called di Brivio. At the distance of about five miles from the Lake of Como, the bed of the whole stream is so confined, tortuous, and rapid, that it is no longer navigable in any way for the space of five miles, as far as the Castello di Trezzo. It is in those parts that they have drawn from the Adda, a navigable canal, called the Canal della Martesana, from the name of the province through which it passes: its length is twenty-four miles, and its reduced breadth about eighteen cubits. At the place di Cassano, they have drawn from the Adda another canal, called della Muzza, which, by the great number of its branches, waters and enriches all the plains of the Lodesan.

VIII. According to the report of Sigonius, in his History of the Kingdom of Italy, Book XIV., year 1179, it appears that the upper trunk of the first canal of the Tesino, to the Place di Abbiate, had been made long before by the Pavese, to irrigate the adjacent plains. According to Corius, the continuation of the same canal from Abbiate to Milan was begun in 1177, fifteen years after the dismantling, or as is commonly believed, the destruction of that town by Frederick Barbarossa. As the testimony of Corius, the first of all the Milanese historians, is very clear, it appears that what is read in the Chronicle of Bossi, year 1257, what was said afterwards by Jovius in the time of Martin Torriano, and what is added by the same Corius, under the year 1272, of the preparation made under Nappo Torriano and Otto Visconti to excavate the mouth of the canal, and to lead it conveniently into the city, are to be understood not of the commencement, but of the continuation and completion of the whole work.

IX. Most writers, and especially the Ultramontane, have fallen into an error in asserting that the Canal della Martesana is the work of Leonardo da Vinci, and that it was made in the time of Louis XII. and of Francis I. This canal was made in 1460, under the Duke Francis Sforza, as is attested by Peter Candido Decembrio di Vigevano, a contemporary author, and as may be seen in Vol. XX. of the Writings on Italian Subjects, Col. 1046. The immortal Leonardo merely joined the two canals towards the end of that century. The Canal of Martesana, when first constructed, did not contain so great a body of water; and it was used for navigation only two days in the week, when the openings for irrigation were shut. In 1573, under the government of the Duke of Albuquerque, the body of water was augmented, and the whole canal established on its present footing, as may be seen in the report printed by Settala.

X. I have never cast my eyes on these Canals without feeling high respect for these illustrious architects, who found means to overcome so many obstacles. It was requisite, in both of them, to erect very great works at the entrance of the water, that the constant supply of a sufficient quantity might be secured; and then it was necessary to construct several regulators to let off the superabundant waters from the freshes of the Tesino and of the Adda, as well as from some torrents that entered them with open mouth. The first canal is supported, for several miles, by a stone dike; and for several more they were obliged to excavate through a very high bank. It was indispensable to conduct the second, for the space of five miles, along a declivity, and to cut its bed through the rock in several places; and afterwards to support it, on the

left, by a dike of stones and earth, at the height of forty braces above the bottom of the Adda, which flows close to it upon a precipitous slope. It was further necessary to carry it across the torrent Molgora, by means of a stone bridge of three arches, and to permit it to be crossed by the river Lambro, which enters and flows through it with all its floods.

XI. But how useful soever and extensive such works, even in their first origin, might have been, their navigation remained very imperfect till the invention of those supports which the Italians usually call *Conche*, and the French *Sas*, and *Ecluses à porte busquée.** The ancients had a method of moderating the too great declivity of rivers, and of retaining the necessary quantity of water, by means of certain sluices, which were opened when they wished to let boats pass through. Belidor has described them in his Hydraulic Architecture, Book IV. Chap. iii. It appears, that they resembled the two sluices constructed at Governolo, in the years 1198 and 1394, to support the waters of the Mincio on the Mantua side. When the Chinese wish to join rivers of very different levels, they sustain the beds by strong sluices, and form there great cataracts; they then provide the machines that are requisite to raise up the vessels to the level.

XII. The Chinese sluices render the navigation very difficult and incommodious, and those of our ancients are of no use where the fall is very great, and when it is required to remove vessels from one canal into another that is much more elevated. The doubling of the gates, and the contriving to raise and lower the level of the water within the enclosure, was the epoch when the last decree of perfection was given, in

* With us they are termed *Locks*.

Europe, to the art of navigating rivers and canals. For, by opening the lower gates, and causing the boats to enter between them and the upper, and then shuting the former and opening the dischargers of the latter, the waters flow in, and gradually rise to the level, at which the upper gates can be opened to afford a passage into the higher canal. By working the contrary way, the vessels are returned with equal facility into the lower cut. In this manner the waters, within the enclosure, are brought at pleasure to the level of the two canals. The difference of the greatest and least heights is called *the fall of the sluice.*

XIII. The sluices with double gates were invented and carried into effect, for the first time, on the Brenta, near Padua, in the year 1481, by two engineers of Viterbo, of which circumstance Zendrini has preserved the memory in the twelfth chapter of his Book on Running Waters. Leonardo da Vinci instantly availed himself of this great invention, to form the junction of the two Canals of Milan; and by means of six locks, having, in the whole, a fall of seventeen braces, he rendered the navigation, from the one to the other, free and commodious. The work was completed in 1497, under Louis the Moor, as may be seen by the inscription placed on the side of the last sluice, where you read as follows:—*Cataractam in clivo extructam, ut per inæquale solum ad urbis commoditatem ultro citroque naves commearent. . . . . .Anno* 1497. The invention of these locks produced, moreover, the continuation of the navigable canals of Bologna, of Modena, and of several others in Italy; and, above all, it gave rise to a system of navigation generally practised, and well understood, throughout the Venetian States.

XIV. The first locks that were ever erected in France are those of the Canal of Briarre. This canal was begun in the time of Henry IV. and the Duke of Sully, and was completed under Louis XIII. and Cardinal Richelieu. Its length is eleven French leagues, and it forms a communication between the Loire and the Loing, which is one of the tributaries to the Seine. Under Louis XIV. another canal was drawn from the Loire, near Orleans, which flowed to meet the first Canal of Briarre near Montargis; and as in summer there was an insufficiency of water in the Loing to supply a commodious navigation, under the minority of Louis XV., they determined to run another canal all along the banks of the river to the vicinity of the Seine; and this, properly speaking, is the continuation of the old Canal of Briarre. In this canal there are, in all, forty-two sluices; and in that of Orleans twenty. In the reign of Louis XV., and under the inspection of the celebrated Belidor, was formed also the Canal of Picardie, forming a junction between the Somme and the Oise, which afterwards enters the Seine about five leagues from Paris.

XV. This art has never been carried to a higher pitch than in the famous Canal of Languedoc, which forms a communication from the Mediterranean Sea to the Garonne and the ocean. Boats pass in eleven days from the one sea to the other, traversing valleys and mountains, and ascending to the height of 600 feet above the level of the two seas. The harbours of Bourdeaux and of Marseilles avoid, by this means, a circuitous route of communication of upwards of eight hundred leagues. This great undertaking, projected under three other kings, was at last perfected in the reign of Louis XIV., after a labour of fourteen years,

at an expense of eleven millions of livres, without reckoning the additional expense of two millions more, incurred in re-establishing the harbour of Cette. Andreosi first suggested the plan, and Riquet directed almost the whole of its execution. He began the work in 1666.

XVI. This canal begins at a lake nearly four miles in circumference, which, collecting the waters of Mont Noir, conveys them, at Naurose, into a grand reservoir, 200 toises in length by 150 in breadth; whence the waters are distributed to the right until they meet the Garonne, near Toulouse, and to the left as far as the Lake of Tau, which is near the port of Cette. The breadth of the canal is 30 feet, its length 125 miles 680 toises, which make 50½ French leagues. Nearly a sixth part of this canal is carried over mountains deeply excavated; and, at a spot called le Mal Pas, it crosses a rock cut into the form of an arch, 80 toises in length, 4 toises in width, and 4½ in height. It has 100 sluices, and a great number of aqueducts and bridges. They have laterally introduced several secondary canals, which both extend and facilitate the inland commerce of the southern provinces of France.

XVII. It is to Marshal Vauban that they are indebted for the perfection of this canal: equally great in the studies of peace and of war, he successfully applied to it, in three hundred and thirty-three instances, the hints which he had found scattered unproductive in the writings of the Italians. Riquet had committed an essential fault in its first construction, when he permitted various torrents to enter it, without taking any precautions against the substances which these torrents and the rains might wash down from the

mountains. At the end of twenty years the grand Reservoir of Naurose, as well as the canal itself, was in a great measure filled up. Marshal Vauban, in the first place, caused a new canal to be opened, to avoid the necessity of the boats passing through this reservoir. He then, by means of six canal bridges, and thirty-nine subterraneous aqueducts, turned from the canal all the influent streams that had carried into it coarse materials. And, lastly, he opened discharging sluices along the whole line, to lay the canal dry whenever it required repairs. This example is too luminous not to be preserved as a memorial of what should be done in similar cases.

XVIII. If the junction, made by Peter the Great, of the Baltic with the Caspian Sea, has not equalled the Canal of Languedoc in the science shown in its construction, it certainly surpasses it in extent of navigation. The whole of this work is now completed; and Marshal Munich has had the glory of putting the finishing hand to it. Vessels from the Caspian ascend the Wolga a very great way above Casan, and then pass into the Tuertsa, which is one of its tributaries. It is here that the canal begins, which flows into the river Sna, by which you descend first into the Mesta, and thence into the Wolkowa; afterwards, into the canal which runs along the banks of Lake Ladoga; and lastly, in the Neva, to Petersburg and the Baltic. They have also made another canal, which establishes a communication between the Wolga and the river Don and the Black Sea. In Poland, they have opened another communication from the Baltic into the Black Sea, by means of the canal that joins the Vistula with the Boristhenes.

XIX. The junction of the Oder and the Spree is

the work of Frederick William, surnamed the Great Elector. The most ancient canal in Flanders is that which goes from Brussels to the Scheldt, a work of the beginning of the last century. The canal, by which the Meuse communicates with the Rhine, was begun in 1626. It will for ever be remembered, in history, for the manner in which the Marquis of Spinola protected the execution of it. The canal from Ghent to Ostend is the work of the present century. As the rivers in the Low Countries do not carry coarse substances, have but little slope, and run on planes of nearly the same level, it is a very easy matter to render them navigable, to unite them, and to derive from them numerous navigable canals. This, however, does not prevent Holland from exhibiting, in the multitude of its canals, a very interesting and uncommon spectacle to the eyes of a philosophical traveller.

XX. There are several other great projects of this description that at present engage the attention of the most polished and enlightened nations of Europe. In France, it is proposed to form a junction between the Saône and the Armançon, one of the tributaries of the Yonne; and, by this means, to form a communication between the Rhone and the Seine. In Spain, some Italians have had the merit of forming a navigation from Madrid to Aranjuez. In Ireland, they are constantly extending the navigation of the river Shannon into the heart of the kingdom. In Scotland, near Glasgow, the two seas on the east and west run so far inland, that they leave an isthmus of but a few leagues to pass from one frith to the other. The rivers that fall into these friths might facilitate the construction of a navigable canal, which would

save the long and dangerous circuit of the northern coasts. This work is going on.

XXI. In England, the Duke of Bridgewater has, within these last years, left a monument of his enterprising genius in the canal which passes from the town of Liverpool to Warrington; and, after running for a considerable distance under a mountain, leads to his coal mines, and to Manchester. This example could not prove sterile in the country of Elizabeth and of Newton. The nation that, by a glorious war, is become mistress of the most distant seas, has employed herself during peace in forming a more easy communication between the seas that are near her. They have begun a canal near Congleton, to join the Mersey with the Trent and the Humber, and have already overcome the principal difficulty in the undertaking, by forming an arch under a mountain for about a mile and a half. And, that nothing might be wanting to the interior communication of the kingdom, a junction has been proposed between the Trent and the Severn, which flows into the Bristol Channel.

XXII. A still greater project at present occupies the most enlightened nation of the north. The passage of the Sound is becoming more and more difficult, in proportion to the extension of the shoals and the heightening of the bottom of the Baltic. A free communication between the Baltic and the Ocean, through the interior of Sweden, would be the era of the aggrandizement of the commerce of this flourishing kingdom. In its interior there are two extensive lakes, the Wetter and the Wener. They descend from Lake Wetter into the Baltic, by navigating the river Motala. The River Gotha flows out

of Lake Wener, at Wenersburg, and enters the ocean at Gothenburg. If the navigation of these two rivers could be rendered commodious, and the two lakes were joined by a navigable canal, it would afterwards be easy to pass by means of another canal from Lake Wener into Lake Heilmar, near Orebro; from which, in the time of Charles XI., a passage was open into Lake Meler, that extends to Stockholm. A good map of Sweden will at once show all these places.

XXIII. The greatest difficulty attending this scheme consists in rendering the river Gotha navigable a little below Wenersburg, where there is a dreadful pass, called the Pass of Trollhatan. At this pass, the whole bed of the river is so very irregular, and so studded, or rather interrupted, by large rocks, that in three different places it is reduced from its ordinary breadth of 600 Swedish feet* to one of little more than 100 feet; and, as the bottom has a considerable slope, the waters, repelled and confined on all sides, form three great cataracts, of which the total fall is 113⅓ Swedish feet, on a length of about 7000 feet. The human mind was not to be confounded by the fury and impetuosity of a river like this. From the earliest times men have sought the means of making, at the Pass of Trollhatan, a navigation, free, commodious, and durable.

XXIV. In the days of Gustavus Vasa, and of Henry and John his sons, nothing else was either thought or spoken of. Under the third of his sons, Charles IX., they began to do something more: they removed the impediments from the bottom at the place called Carls-Graff. Gustavus Adolphus, almost constantly employed abroad, had no leisure to consider this scheme: his daughter Christina gave it much atten-

* The Swedish foot is about 11½ English inches.

tion; but, as she believed that the work was impracticable at the Pass of Trollhatan, she directed that some other less difficult situation should be selected for the purpose. Charles Gustavus was constantly engaged in wars against Denmark and Poland. Charles XI., despairing of being able to render the river Gotha navigable, and finding the track projected in the time of Queen Christina was too expensive, ordered a third to be traced, which proved equally impracticable. Charles XII., accustomed to surmount the greatest obstacles, sent for the celebrated Polheim in 1716, and soon after agreed with him on all the conditions under which, in five years, he was to render the Pass of Trollhatan navigable, and open a free passage from the Baltic into the ocean. Execution always followed the orders of this enterprising and resolute prince: materials were instantly collected; and the first sluice, half a mile above Trollhatan, was completed, when the death of the king turned aside the views of the public, and otherwise engaged its attention.

XXV. Since 1751, the whole project has been again resumed, but with the adoption of very different measures. It was now determined to distribute the whole fall of 113⅓ feet among three sluices only: the first to consist of 28, the second of 52, and the third of 33⅓. These sluices were to be constructed alongside of the three cataracts, and were to be each 18 feet wide by 72 in length. The work advanced successfully, until they attempted to throw a wear across the river at the gulf of the last cataract, to raise and retain the water above it. The impetuosity with which the whole stream is precipitated had prevented them from sufficiently examining the bottom. They had conjectured, from the nature of the neighbouring moun-

tains, that the bottom must be of rock; and it was further supposed that there could not be more than ten feet of water. Both these suppositions proved erroneous: the depth of the water was from 20 to 25 feet at least, and the bottom was composed of large detached stones, which were incapable of being fixed by any efforts of art. The caissons of stones, although fastened together with cramps four inches thick, and attached by great piles to the mountains on both flanks, were swept off and dispersed by the impetuosity of the current; and, in this manner, all the works were destroyed.

XXVI. The sum of 25,000 sequins annually, which the last diet had assigned for this great enterprise, revived the hopes of better success. It was resolved to avoid this dangerous pass entirely, by means of a fixed branch of water, which should issue from the river Gotha, and afterwards enter it. The whole length of this canal was to be about 8240 feet, and the total fall of 113½ feet was to be distributed, in the space of the last 3000 feet, among seven sluices or locks, each 36 feet in breadth, by 200 in length. The first sluice was to be 17½ feet in height; the others, 16. The first sluice was to stand alone; but the four following were to be close to each other, as were also the two last. Between the fifth and sixth sluice, the canal was to be protected by a strong dike against the floods of the river. There was to be a great discharger between the first sluice and the water entrance, not far from the centre; and at the entrance itself two doors or gates, to lay the canal dry, when required. The annexed plan (Plate II.) will show the track, and the principal difficulties, which were to keep up the bed through a morass for the full space of more than

800 feet, and to excavate the rock in four different places, making altogether a little less than 2000 feet.

XXVII. When, in 1516, Francis I. had made a grant to the city of Milan of the sum of 5000 golden ducats, to be expended in the construction of some navigable canal, a project was in agitation, in some respects analogous to the canal of Trollhatan. The canal that is derived from the Tesino continues the navigation of the upper and the lower trunks of this river to the Lago Maggiore on the one hand, and, on the other, to the Po and the sea, as stated above in paragraph VI. But the canal of Martesana originates in a trunk of the Adda, of which the bottom is so steep and so irregular for upwards of six miles, that one cannot ascend to the upper trunk of that river and the lake of Brivio, from which the Adda begins again to be navigable as far as the lake of Como. See paragraph VII. The nature of a great river, flowing unequally, and on a very great slope, between mountains, was not able to damp the courage of the ancient architects. Pagnani has left us, in a small work, all the details of the plan, which was concerted in 1519 by the engineers Massaglia and della Valle, after a public inspection.

XXVIII. In the first place, they made no objections to the removal of certain great masses which obstructed the navigation of the Adda in the vicinity of the Castello di Trezzo. Nevertheless, in this case, and in others of a similar kind, it is of importance to be cautious, and to remove nothing but what actually impedes the navigation, neither clearing out the bed of the river too much, nor rendering its course more free than is absolutely necessary; because, in general, the rocks and the stones that impede the flow of a river, perform the functions of so many natural wears,

by retarding the current, and detaining the gravels and the other coarse substances. When the bed of a stream is set free from every impediment, and the force and impetuosity of its waters are consequently increased, the river must necessarily carry into its lower trunks a much greater quantity of gravels. I have sufficiently explained these principles in the First Book of the Treatise on Rivers and supported them also by the examples of the changes that have happened, during this century, in the Arno and the Reno. The attention, which it is necessary to bestow on the lower canals of irrigation, will always justify the precautions that have been suggested to prevent the spreading of the gravels, which the Adda already brings down in such abundance in the time of its floods.

XXIX. The obstructions of the rocks once removed, the Adda might be ascended for five miles above the place where the water enters the canal of Martesana; so that the chief obstacle to continuing the navigation to the Lake of Como would be reduced to the sole but most critical space of about 4280 braces lying higher up. The whole bed of the stream, in this space, is so very irregular, so steep, and so studded with rocks, that it is impossible to pass along it without danger. According to old levels, which we have for the whole of this space of 4280 Milanese braces, making about 8577 Swedish feet, the total fall is 46 braces, which make 92½ Swedish feet. The principal difficulty here, then, is to divide these 92½ feet of height on a length of 8577 feet, as in the Swedish Canal, and at the Pass of Trollhatan, described above, it was to distribute 113⅓ feet of fall on a length of 8240 feet.

XXX. As these first engineers despaired of being able, by all the assistance of art, to render the bed of the river navigable through a pass of this nature, they proposed to run a fixed branch from it, by excavating a canal of 18 braces in a little valley contiguous to the Adda on the right, called della Rocchetta, and to compel the water to enter it by means of a strong sluice, 7 braces deep, and supported by three rocks called the Three-Horns. The plane of the valley of Rocchetta is disposed in such a manner, that for the first 3220 braces, in descending, the whole canal would be sunk in the earth: in the next 1060 braces the surface of the ground is lower by 18 braces, and there remains a descent of 28 braces more to reach the bottom of the Adda. Massaglia and della Valle proposed to make four locks, each $4\frac{1}{2}$ braces in height, to take up the fall between the two first levels, so that they might not be compelled to restrain the canal within embankments for the space of the last 1060 braces; and they proposed, further, to descend into the Adda by six other locks of an equal height.

XXXI. Towards the end of the sixteenth century, when the work was to commence, the engineer Meda proposed, instead of ten locks, to make only two, the one 30 braces in height, the other 15; so that, on this occasion, there occurred exactly the reverse of that which was projected in the case of the Swedish Canal, where they began with proposing very high sluices, and then adopted the expedient of increasing their number, and consequently diminishing their height. The walls of the two locks of the Adda were constructed a few years afterwards under the direction of the engineer Barca. The excavation was then made as it now appears; and, according to some plans that

I have seen, they also erected a sluice, which crossed the bed of the river. I have not, indeed, found any memorial of the accident that destroyed the sluice, and rendered the excavation useless; but, after a personal inspection of the spot, I have inferred the existence of what might probably have been the fact.

XXXII. The ground in those parts is composed of gravel, sand, and earth. Under the surface of the plains in the vicinity, and on the sides of the mountains between which the Adda flows, the soil is no longer so loose, and it there begins to have some consistency. It afterwards forms, in the bed of the river, a species of sandstone of which the hardness is unequal, and not very great, and which is vulgarly called *morogna.* The valley of Rocchetta being very narrow at its entrance, it was not possible to keep the excavation very distant from the Adda for several hundred cubits below the opening to admit the water: and, as it was absolutely requisite, for the convenience of the navigation, that the canal should be nearly horizontal, it became necessary to keep it always gradually higher than the very sloping bottom of the Adda, which was quite contiguous to it. This being admitted, any crack that accidentally opened itself in the left bank, or in the bed of the canal, would very soon be enlarged by the impetuosity of the waters, to which there was, on one side, a precipitous fall into the river. I believe that it was precisely in this manner that the deep and spacious hole which is found a little below the entrance of the water into the canal was formed. The waters being thus turned into the Adda, they were obliged, that they might avoid the evils of the floods, to demolish the sluice, and to re-establish the river in its primitive state.

XXXIII. I was witness to a similar accident, which

happened in the Canal of Bologna some years ago. The waters opened themselves a passage through a hard bed of sandstone, in which the opening of the canal is dug, a little below the sluice of Casalecchio; and having, at this place, a very great fall on the bottom of the Reno, which is contiguous, they soon very much widened the breach, and would have ruined the navigation, if a speedy remedy had not been applied, in a thorough repair of the damage, at a heavy expense, by means of a double wall of stone and pozzolana. Therefore, in the case proposed, and in all other similar instances, where it is required to make a horizontal excavation through bad ground or a loose soil, and near a stream of great declivity, it is essential to the security of the undertaking that the side of the canal nearest to the river should invariably be supported by a strong stone embankment, precisely as is done in the first trunks of the two other canals of Milan.

XXXIV. Pagnani has, moreover, left us, in the treatise before cited, an account of the levels, and other operations of art, undertaken by former engineers, to ascertain whether some navigable canals might not be projected in Lombardy; and, above all, to determine the practicability of joining the lake of Como with the neighbouring lakes. In the first place, they found that the surface of the lake of Como was 48 braces lower than the surface of the lake of Civate, 62 braces lower than that of the lake of Pusiano, and about 100 braces below that of the lake of Lugano. Further, that the lakes of Como and Lugano are, at the point of their nearest approximation in the valley of Porlezza, about six miles distant from each other; and that they are separated by a very high ridge, which would render any attempt to open a navigable

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canal very arduous, even independently of the very great difference in the levels. The general map of Lombardy will, on a slight inspection, show the places, without requiring the addition of particular surveys.

XXXV. The same engineers found, that the scheme of running a canal from the lake of Lugano, by the valley of the Olona to Milan was impracticable. It might, however, be possible to render the Olona navigable below Tredate, provided the waters were retained in the last trunk by means of some well situated locks, and the upper mills were so placed as not to interrupt the bed of the river. In the project to render navigable the Tresa, which is the outlet by which the lake of Lugano discharges itself into the Lago Maggiore, these engineers found difficulties from the deficiency in the body of the water, and from the too great slope of the Tresa: to which it may be added, that several torrents which enter it carry into it stones and gravels. But it is very strange that these engineers never thought of another project, of which the execution would be very easy, as well as very convenient, and highly useful: this is, to make navigable the Boza, which is the outlet of the little lake of Varese into the Lago Maggiore.

XXXVI. The scheme of conducting a navigable canal from Milan to Pavia is of a much older date: it would be the shortest way of joining the two canals of Milan with the Tesino, the Po, and the sea. Galeazzo Visconti, the father of Azzon, began its excavation: they even constructed the walls of a great sluice, such as they are still seen at present. In 1564, the completion of the work was made the subject of considerable discussion. It was imagined that the

expense could not be very great; and that, by giving the sluices the common height, a great number would not be required. The enterprise was abandoned afterwards, because the canal of Bereguardo, although it did not reach the Tesino, was found sufficient to keep up the commerce between the two cities of Milan and Pavia. Pagnani, in the same treatise, mentions some other projects of a similar nature, to which we deem it unnecessary to advert.

XXXVII. In Italy, another great undertaking has been agitated: namely, to render the Tiber navigable from Ponte-Nuovo, below Perugia, to the entrance of the Nera, from which the navigation begins to be free, and without interruption, to the sea. MM. Bottari and Manfredi have given an able Report of an inspection which they made of the Tiber in 1732. In this Report they laid it down, as a first principle, derived from experience, that to navigate any river with facility, particularly against the stream, it is requisite that the slope should not exceed three Roman palms* per mile. Now, as the fall of the Tiber is 8 or 9 palms, they calculated that it would be very difficult to steer the boats down the river, and still more difficult to conduct them up against so rapid a stream, especially in some places, where the fall was even greater, and where, consequently, the stream must for ever remain impassable. They, moreover, pointed out very clearly the difficulties and the dangers which must be encountered in adopting the different expedients that had been proposed for reducing the excessive slope by wears, for removing the detached stones by manual labour, and blowing up the obstructing rocks by mines, and for improving the bed, in

* The Roman *palm* is about 8½ English inches.

certain places, by changing its course, or by contracting or enlarging its dimensions.

XXXVIII. The schemes for rendering the bed of the Tiber navigable having been thus refuted, they inquired, in the same Report, whether a canal, for boats of a moderate size and suitable burden, might not be formed exteriorly to the river; observing the nature of the soil through which the canal must pass, the frequent crossings that would be required from one side to the other, the number of dikes and sluices that would be wanted, and the other works that would be necessary to secure the navigation against all accidents, and particularly those from floods. These very authors concluded, that this undertaking ought to be regarded as of very difficult execution; and they advise that it should be abandoned rather than attempted. They next examined the plan of making the Tiber navigable to Rome, proposed by the engineer Chiesa, in his Report printed in 1745.

XXXIX. Eustace Manfredi has left us some things in this first Report, which may serve as rules in similar cases. Several other writers have treated on Navigable Canals in general, and chiefly Guglielmini, in chapter twelve of his book on the Nature of Rivers, and Belidor, in Book IV. of his Hydraulic Architecture. That which Belidor has stated in the first paragraphs of chapter seven and we have mentioned in paragraphs XXXII. and XXXIII., will suffice for the principal elements of the excavation of canals. To reduce to its first principles the scientific part of this very important subject, we will consider, in their order, 1st, The derivation of the canal. 2d, The regulation of the quantity of water. 3d, The clearing out of the bot-

tom. 4th, The construction of the sluices. 5th, The distribution of the slopes.

XL. Navigable canals are formed, either by collecting in them the waters of springs and rains, or by deriving them from some river. In the first case, which is that of some canals in France, it is requisite to examine fully the nature of the springs, as well as to ascertain the quantity of the evaporation, and of the rain that falls, so as to ensure the quantity of water required. In the second case, which is that of almost all other canals, it is usually necessary that a sluice or dike should be thrown across the bed of the river, to compel a portion of its stream to flow constantly into the opening of the canal. When the water in the rivers is not very abundant, or their bed is too free and too wide, or they can turn the current of their stream this way or that way, according as the deposits of the gravels may have been left on the one side or the other during their floods, it becomes necessary to impose on them certain restrictions, that they may be made to furnish a supply, at all times, to the canal, adequate to all the purposes of the navigation.

XLI. The most extensive work of this nature that I have ever inspected, is the wear at Casalecchio, which serves to turn the Reno into the Canal of Bologna. The Canals also of Martesana and of the Muzza are derived from the Adda by other great sluices; but the great Canal of Milan begins without the usual assistance of sluices, and its bottom spreads itself forward over that of the Tesino. The first engineers, unwilling to interrupt the free navigation of the river by a sluice, found means to draw from it a fixed branch of water by works of a different description. The Tesino, a large, rapid, and irregular river, which, in

other places, both above and below this, often changes its bed, as all rivers do that carry gravels, is here so enclosed between its dikes, that it never fails to supply the required quantity of water to the canal. I have had occasion to be at this place several times during the floods, and I have been astonished to observe with what impetuosity and fury these works were assailed by the current.

XLII. The nature of the spur, which defends and secures the angle of derivation of the waters of the canal from the Tesino, formerly underwent great changes. Sometimes the Tesino threw its whole stream into the canal, and interrupted the navigation by the accumulated gravels which it left deposited in the bed; at last, in 1585, after a great flood, which came down on the 7th of August, the city being destitute of provisions, the spur, by the advice of the celebrated engineers Bassi, Pellegrini, and Meda, was repaired and lengthened. At this time, it received the shape which it at present retains; and those works were constructed above it which yet exist on the right and left shores of the Tesino, and which, as they are still to be seen, it is unnecessary to describe. Although an apprehension, that the Tesino might recede too far from the canal, gave rise to the very difficult plan once in agitation of rectifying and changing the bed of this river, the experience of the past serves to assure us, that the present works will yet serve for a long time.

XLIII. In other ordinary cases, when a fixed branch is to be drawn from a stream to continue a navigation that is not practicable in the bed of the river itself, the work must begin with traversing dikes or wears. The general rules for erecting them are very accurately laid down by Bacciali, in a Dis-

sertation printed in the fourth volume of the Proceedings of the Academy of Bologna. In the case of which we are now speaking, great care must be taken that the height of the dike, and the depth of the water that is to flow into the canal, may be the smallest possible, consistently with the uses of the navigation; not only that less height may be given to the sluices, but also to diminsh the labour that would be required to support the sluices, the banks, and the dike itself, against the increased pressure of a greater body of water. This is an important precaution, but it is not the only one that must be employed to prevent navigable canals from being overcharged in the time of floods.

XLIV. In the canal which, at Pisa, forms the communication between the Serchio and the Arno, and which is believed to be the work of Lorenzo degli Albizzi, I have observed the skill with which they have contrived to prevent the great freshes of the Serchio, although they are very heavy, and come down in a few hours, from throwing more water into the canal than is necessary, by constructing, at Ripafratta, very strong sluices, which are easily thrown open. All this mechanism was requisite at this spot, because the canal, for a long space, is so encased, and, as it were, buried in the land, that there is no vent or outlet for the waters. In a canal which is to carry a large body of water, and which must necessarily run in almost the same direction with the stream of the river, as in the canal projected for the higher branch of the Adda, all works, opposed in front to the impetuosity of the stream, would be useless. The only plan to be adopted in such a case is, to let all the superfluous waters flow over the banks of the canal

into the river. This is precisely the manner in which the other canals of Milan are constructed: free entrance being given to the water, they are flanked, for a considerable distance from their head, by an embankment, over which the waters flow when the floods exceed their ordinary height.

XLV. But these precautions are not sufficient for those waters which may be thrown too far forward by the impetuosity with which they enter the canal; or for those which fall from the neighbouring heights, or are brought down by other tributary streams. To release itself of these, the whole canal must be furnished with adequate discharging outlets. The canals last mentioned are also well provided with these, that the highest floods of the Tesino and of the Adda can never cause any damage, if care be always taken to adjust, in good time, the sluices at the head, and to open the outlets along the lower parts of the canal. In the Canal of Martesana in particular, there are, both above, below, and opposite to the entrance of the Lambro, nineteen outlets, placed with so much skill, that they suffice, not only to let off all the floods of the Lambro, but even to discharge half the waters of the canal besides, or nearly that quantity; so that the torrent Seveso, of which the capacity is reckoned to be nearly equal to half the volume of the canal, on entering it a little lower down, does but raise the body of water to the usual height. The ancient discharger, at the place called Mondrone, to which the overflow of the Lambro extends, and where the torrent Molgoretta enters the canal, had been destined for the same purpose.

XLVI. The floods of the Adda occur generally in summer, in consequence of the melting of the snows on

the mountains. The Seveso, the Lambro, and the Molgoretta, of which the courses are neither so long, nor run so far back among the mountains, commonly swell in summer from storms, and in the autumn from heavy rains. To prevent all accidents from the floods, when they descend at the same time, and to supply the defect of the outlets, which might happen not to be opened, they have taken an excellent precaution, by making all the redundant waters, before they reach Milan, discharge themselves into the outer ditch of the town named Redefosso, into which they fall through six spacious gates, as from the top of a sort of precipice. The waters of the Redefosso, after different ramifications, flow at last either into the Lambro, or into the Canal della Vecchiabbia, which is the chief vent for the waters of the two canals reunited, after making the circuit of the town. The detail of the ramifications would not be interesting to strangers, and it is sufficiently well known at Milan.

XLVII. We have very accurate observations on the causes of those inundations from the floods, which, in times past, incommoded several quarters of the city. Since 1761, by taking merely the common precautions of regulating and opening, in proper time, the outlets of Loncesa, Vaprio, and the Lambro, no overflow has taken place, although, in the months of May and June of that year, it rained incessantly for forty days; and two very great floods of the Seveso and the Lambro came down within a few days of each other. The same thing happened in the spring and the summer of the following year; and in the month of November, when all the waters of the Redefosso overflowed the quarter of the Tosa Gate, it was assertained that the outlets of the Lambro had been left shut, and the inundation

ceased the instant they were opened. Experience thus clearly shows, that this quarter may be secured against all inundations whatever, provided that, on the first signs of a flood, the proper use is made of the sluices. The inundations on the side of the Roman Gate are occasioned by accumulations in the ditch by which the Redefosso empties itself into the Vecchiabbia, and by other obstructions to its course, which it is unnecessary to mention.

XLVIII. The first engineers, after having thus provided against accidents from the floods, considered next the means of keeping the upper beds of the two canals perfectly free from gravelly deposits and other coarse substances; but, with respect to the accumulations on the bottom in all the lower trunks, and in the circuit of the city, they suggested no other expedient than the application of manual labour. The science of rivers and of navigable canals would be greatly simplified, if the waters were always limpid and clear: it is the substances intermixed with them that form the principal difficulties. In the present case, it has been frequently under consideration, whether it might not be practicable, by some other means, to provide for this branch of the Civil Police, and to guard against the evils of bad air, in avoiding the inconvenience of cleaning out, from time to time, the whole canal. It has even been proposed to leave all the sluices open on holidays, when the mills are not worked, and then to stir up the bottom with rakes, that the waters, running swiftly into the vent of the Vecchiabbia, might carry into it all the deposits. But it would not be an easy matter to stir up the whole bottom; and the readier mode, of leaving all the sluices open, would not, perhaps, supersede the

necessity and inconvenience of clearing out the canal by manual labour.

XLIX. The two first sluices which are met with in descending the Canal of Martesana, in the city, are 500 braces distant from each other. The last sluice is distant from the outlet of the Vecchiabbia about 1500 braces; and below this outlet there is another branch of the canal, 3756 braces in length, in which there is no sluice. In this manner, although the outlet and the sluices have each a fall of some braces, and the whole fall, from one end of the lower ditch of the town to the other, is very considerable, the total slope, nevertheless, is not uniformly distributed; and, for several long intervals, the lower ditch does not partake of it in any degree whatever. When once they shall have cleared out the whole channel, and afforded a free course to the stream, this course will become slower between the first and the second sluice, and between the last and the Canal of Vecchiabbia; and hence the substances brought down from those places where the fall is greatest, will accumulate, and the waters, forming of themselves a new impediment, would gradually lose the force required to carry other substances further on. Thus, since manual labour cannot, on this plan, be avoided, the best measure to be adopted would perhaps be, to render it more commodious, by making continual use of some of those machines which are employed both in France and in Italy, and which are found sufficient to preserve the necessary depth in several harbours and canals.

L. They have sufficiently provided for the clearing out of the beds in the upper trunks of these two canals, where stones and gravels are brought down in great abundance with the stream, by placing in

them a number of discharges sufficient for the purpose, called *bottom* or *ground sluices.* This sort of outlets should be constructed in the bank of the canal, on the side nearest the river, in such a manner that their sills may be considerably lower than the bottom of the canal itself. The waters, that are occasionally suffered to precipitate themselves into the river from such apertures, acquire great velocity; and those which pass being accelerated, those which follow are accelerated also, by reason of the adhesion and tenacity natural to the particles of water. As this acceleration extends a considerable way from the opening, the grosser substances not only are detached from the bottom, but the excavation also is prolonged to a distance from the opening. With several sluices of this kind, which are opened at proper times, and which are so distributed, that, at the spot where the action of one ceases, that of another begins, the gravels, which had entered the canals, are forced to throw themselves again into the river in the least space of time possible.

LI. Some authors have proposed expedients to prevent any sort of gravels from entering into canals. Eustace Manfredi, in treating, as it is said, on the means of drawing from the Tiber a fixed branch from Ponte Nuovo to below Perugia, proposed the construction of a wear, of eight Roman palms,* which, in consequence, raised the surface of the water eight palms. He directed also that the sill of the entrance at the head of the canal should be five Roman palms† below the heightened surface of the river, so as to retain in the canal the sufficient depth of five palms of water; and, by the three redundant palms,‡ to pre-

* 5 ft. $10\frac{1}{4}$ in. English. † 3 ft. $7\frac{9}{10}$ in. English. ‡ 2 ft. $2\frac{3}{10}$ in. English.

vent the introduction of any pebbles. Further, he considered how the bottom of the river might be prevented from rising above the wear; and he thought that this might readily be effected by the formation of openings, to be closed with planks, boards, facines, or other moveable substances, to be used in the time of floods. And, finally, in the detail of the scheme, he pointed out the several precautions that should be taken to turn aside all the tributary streams, by which any gravel might be thrown into the canal, as taught by Guglielmini, in the twelfth chapter of his Book on Running Waters.

LII. Belidor, in the sixth chapter of his book above quoted, has suggested the idea of receiving the waters into a great reservoir, in which they might deposit their gravels, and other coarse substances, before they entered into the canal; but, although this plan has been practised in the famous Canal of Languedoc, it is always liable to the objection, that it is extremely difficult, and extremely expensive in the execution, and never applicable to any case in which it is necessary to draw a fixed channel of water from a great river running between mountains, or of which the banks are very high. Manfredi's expedient must always fail in rivers whose course is rapid, and which carry great quantities of gravel, as do the Reno, the Adda, and the Tesino; because, according to some experiments of Father Grandi, the specific gravity of gravel in water is to the specific gravity of water itself nearly as 5 to 3, and this small difference of density and specific weight is very easily to be balanced by the transverse impetuosity of the stream: whence it happens that the gravels, even of the coarsest sort, often beat hard against the tops of the highest wears,

and even pass over them, and fall into the lower trunks. It is therefore evident, that, in these cases, the proposed expedient will not prevent the gravels of a river from being conveyed to a great distance in a contiguous canal.

LIII. Bacciali, in the Dissertation which we have already mentioned, has proposed, as a preventative to the filling up of the canal, to open, in the thickest part or body of the wear itself, beneath the bottom of the mouth of the canal, some channels, through which, in times of floods, the gravels might be forced, and so be retained in the bed of the river. This expedient was successfully put in practice at the sluice of Casalecchio, where it serves chiefly to lay the canal of the Reno dry, whenever it is necessary to clean it out, thus superseding the use of machinery for the purpose. The height of this sluice or wear is 26 Bolognese feet. But, in the first place, one seldom meets with that combination of circumstances, in which it is necessary, and possible, to raise the wear high enough to leave space sufficient to place the channels below the level of the bottom of the canal. And, besides, with respect to this very sluice of Casalecchio, although a great quantity of gravel is driven forward through the channels, still this does not prevent a great number from passing into the canal; so many, indeed, that it has become necessary to construct some bottom sluices to prevent the bed from being filled up.

LIV. The canal of Bologna has below its inlet, at various distances, several outlets, on a level with the water, constantly open; and also six bottom-sluices, which are opened in times of floods. The surface-sluices permit all the waters that rise above the

common height to fall over into the Reno: and the trellises, or gratings, of the bottom-sluices, make them operate at once as gates and clearers; because, when they are closed, they cover the bottom as far up as the flood-gates built into the walls; and then, during the floods, when all the vents are opened, the impetuosity of their stream serves to keep the bottom sufficiently deepened. Guglielmini has recorded, in his twelfth chapter, that although, in his days, the gravels extended in the bed of the Reno for five miles below Casalecchio, yet in the canal they reached only a little more than half a mile, and that they might have been reduced within less space, if the ground-sluices had been better placed at the first, and been more frequently used at proper seasons.

LV. In the Canal of Martesana, the gravels extend five or six miles, and the bottom-sluices are so advantageously placed, that they generally suffice to keep the entrance and the first trunk sufficiently clear. The gravels extend much further in the other great canal, and the ground-sluices are so far distant from the entrance, that it is sometimes requisite to employ art to remove those impediments, which the nature of the river opposes to the navigation. Near the mouth of the Muzza, there is a discharger level with the water, and, two miles lower down, there are two bottom-sluices, each having ten apertures: when set to work, they are not felt in the upper trunk, and it is often necessary to have recourse to art and manual labour to remove the heaps of gravel that from time to time diminish the body of water, and excite apprehensions for the factitious fertility of the Lodesan. As the Canals of Martesana and of Bologna are of a more recent date than the other canals, the inconveni-

ences of the more ancient canals have been avoided in their construction.

LVI. In case it were proposed to draw from the upper trunk of the Adda a fixed branch of water, to continue the navigation as far as the lake of Lecco, as has been mentioned in the XXX. and the following paragraphs, any of the expedients proposed in the LI. and LIII. paragraphs would be inadequate to prevent the gravels from extending themselves the whole length of the canal; the reasons of which are, that the surrounding country, as well as all the heights between which the Adda flows, are quite full of gravels; that the bottom of the Adda itself is entirely covered with them, although in some parts, where the slope is greatest, those which fall in from the sides, and the higher districts, are not found to stop there; that the stream descends with extraordinary impetuosity, and that its thread would enter the opening of the new canal almost in a direct line. Now, as in the existing Canal of Martesana, and in the bed of the Adda, the gravels extend as far as the dike of Trezzo, it is certain that, in a place where the fall is greater, and lying in the direction of the thread of the stream, the gravels will naturally be carried down to the distance of a mile, or of a mile and a third; and, consequently, they will be spread throughout the whole of the excavation.

LVII. Outlets, on a level with the surface of the water, constantly kept open, according to paragraph XLIV. would prevent the canal from overflowing in floods; and, according to the L. paragraph, bottom-gates, advantageously placed below the entrance of the water, and before the first sluice, would keep the bed well freed from gravels, and other coarse sub-

stances, which might have been successively brought down by the great freshes. But this would not suffice for the gravels that reach to the upper and lower gates of the sluice. For, in the first place, although the bottom-gate, opening just above it, were made very large, and with a great fall, the waters, in flowing out, would dispose themselves in one continued curve, from the first entrance of the stream into the canal, as far as to the bottom-gate, and would thus have no effect on the opposite angle, lying beyond the convexity of the curve, between the sluice and the bank, where, in consequence, the gravels would always accumulate. Secondly, as the bottom-gates could not be constantly kept open, it might easily happen that a mass of gross substances might accumulate on and cover the exterior platform of the sluice, and prevent the play of its gates. And, lastly, for the reasons assigned in the LIII. paragraph, it might frequently happen, that these substances would pass over from the exterior platform into the interior, and there occasion, in a twofold degree, the same inconvenience.

LVIII. Aquatic surveyors have not yet treated of the case in which a sluice is to be erected in places where gravels and coarse substances are found. According to Massini, the sluices of the Canal of Bologna, which were made in 1493, are placed in situations to which none but the finest substances ever come. It is the same with regard to the sluices that were finished four years later in the Canal of Milan, as well as in all the other more modern sluices of Lombardy, the Venetian States, and Tuscany, and in all the navigable canals of France and the Netherlands. We have ample experience of the continual inconveniences

and accidents to which such works are subject, from the turbids alone, from the fine sands, and from the slime brought down by the water. Guglielmini, in the twelfth chapter, which we have already cited, and Zendrini, in his twelfth chapter on Running Waters, when treating on the Construction of Sluices, are both of opinion that they should occasionally, from time to time, be left open to prevent the filling up. All encroachments and accumulations are augmented in proportion to the coarseness of the substances deposited.

LIX. I had sought for a long time, in vain, for information respecting some lock which had been constructed in a gravelly position, that I might thence derive some knowledge on this subject. Some months ago, an able engineer * informed me, that, in the province of Berri, there was a sluice placed on the Indre, in a situation where this river still brought down gravels and other coarse substances. He likewise explained to me the contrivances which were employed to keep the bottom clear, and to secure the free play of the several gates. The method pursued was to introduce, whenever it was necessary, the stream of a neighbouring torrent, which swept before it all the gravels that had, from time to time, been brought down and lodged by the Indre within the enclosure of the lock. This example cannot always be imitated in other rivers, and in the canals derived from them; nevertheless, it has furnished me with an occasion for thinking of various expedients, and on the precautions which it would be necessary to adopt if obliged to construct a sluice at a spot that was liable to be obstructed by the diffusion of the gravels. The

* M. Bouchet, Inspector-General of Roads and Bridges.

most natural and the simplest expedient would be the following:—

LX. In the first place, I would open an ample bottom-gate directly above the sluice. Secondly, that the action or play of this clearer might extend to the opposite angle, and that all the gravels, spread over the outer platform of the sluice, might have a free passage through the outlet. I would recommend that the platform itself should slope considerably towards the mouth of the outlet. Thirdly, that the gravels might find it difficult to enter the enclosure of the lock at the time of opening and shutting the gates, the sill of the aperture of the first gates should be raised higher than the level of the outer platform; limiting, however, this elevation to such a point as not to obstruct the navigation when the stream is low. Lastly, to clear the interior platform of the gravel which must occasionally lodge on it, I would give it a sensible declivity, and open on it, at its lowest angle, another bottom-sluice, that might be made to act on it when required.

LXI. In this manner, the lock might be kept always in order, without any interruption to the navigation for the purpose of carrying off the new accumulations of gravel by manual labour. But, in the case of which we were speaking, that is, of the canal to be excavated on the Adda, it would be further necessary to abandon the idea of making great sluices of 30 or even of 15 braces in height, as in Sweden they were forced to give up the plan of a sluice of 52 feet, which make about 26 braces. For my part, I cannot conceive by what mechanism it is possible to move sluice-gates of such an extraordinary size; nor do I see that it would be an easy matter to secure the

foundations of the platforms against the eddies that would be formed by a column of water of so great an altitude. Belidor, in the eighth chapter of his Fourth Book, and Zendrini, in the twelfth chapter which we have already quoted, have sufficiently explained and detailed all the practical rules and precautions that architects ought to observe in the construction of the floors, walls, and gates of sluices. But Belidor lays it down expressly in the third chapter, that when there is a greater height than 12 or 13 French feet, it is always better to multiply the sluices, and to keep them united and contiguous, to save the expense of multiplying the gates.

LXII. The sluices in the canals of Briarre, of Orleans, and of Languedoc, in no instance exceed the height of 8 or 9 feet. The eight sluices, that are in the nighbourhood of Bessiers, have altogether a fall of 66 feet, which gives 8¼ feet for each sluice: those of the Old Canal of Picardie are from 6 to 13 feet; and those now constructing on the New Canal, and for the navigation of the Scheldt, will not be above 13 feet in height. The largest sluices in the Netherlands are those of Ostend and of Bouzingue. The sluice which unites the canal of Ypres to that of Furnes, near Bouzingue, is 20 feet in height, as many in breadth, and 120 in length. M. Dubié has shown extraordinary ability in the construction of this work. The eight sluices in the canal of Bologna are, in all, 59 Bolognese feet. The highest sluices in Italy are those at Dolo, on the Brenta. The gates of the sluice at Dolo are elevated 21½ Venetian feet* above the platform on the upper side, and 18 feet 7 inches† on the lower.

* Nearly 25 English feet. † About 21½ English feet.

LXIII. In executing the plan which we have described, for continuing the navigation of the higher branches of the Adda, the sluices might be constructed on the models of those now mentioned. To the last might be given the greatest height, say 10 braces, making use of the walls already built for its construction. Immediately above it, three others, all contiguous to each other, and each about 8 braces in height, should be erected. And, lastly, about 1060 braces higher up, two more, each 6 braces in height, would be required to take up the remainder of the fall, and provide for the difference of the two levels into which the little valley of Rocchetta is divided, as was stated in the XXX. paragraph. The first sluices, on descending, should be lower than those which follow, that they may be the better secured against the great pressure which they must sustain in the time of floods. If to this be added the other precautions, which we explained above, on the construction of the first sluice, and of the bottom-outlets, as well as of those on a level with the stream, I believe that the new canal would be executed in the best possible manner.

LXIV. In the scheme for deriving a navigable canal from the river Gotha, in the manner already explained, it is impossible to determine, better than it has been done, the form, the place, and the dimensions of the seven sluices into which the total fall of 113⅓ Swedish feet is to be gradually distributed. The tracing of the whole canal is such as is best adapted to the topography and the physical situation of the spots where so many various difficulties are to be encountered. The derivation and the return of the stream into the river are both effected at points

where its course is so fixed and bounded by the mountains, that there is no room for apprehending that by any change of course it may either interrupt or retard the upper or lower communications with the canal. The two dikes, which join the little island of Grefon to Melgon, and Melgon to the left bank of the river, and to the lower lip of the mouth of the canal, take in so large a portion of the river, and with so spacious a sweep, that they secure to the mouth the whole quantity of water that can possibly be required.

LXV. The nature of the ground does not permit that the quantity of the water to be admitted should be regulated, as has been done in the canals made at Milan and Bologna: because, as the opening and the first trunk of the canal must be cut through a very high rock, which separates it from the river for more than 300 feet, it will not be possible to force the superabundant waters over the banks, or to open along the shore any outgate on a level with the surface. The most natural expedient, then, will be, to open an ample discharger immediately after leaving the rocks, in a place where the canal is not very far distant from the river. The only discharger which I find laid down in the plans, is too remote from the head of the canal; and although it were made in the form of a bottom-sluice, and with a great fall, it could not produce any effect on the first upper trunk, either by affording a vent for the superfluous waters in floods, or by clearing the bed from the substances brought down and deposited upon it successively by the stream.

LXVI. But, in reference to the quantity of water required, it will be necessary, considering the singular construction of this canal, to observe some other very

particular precautions. On casting a look over the plan, it appears that the whole of that part of the Gotha which is included between the islets Melgon and Grefon may be regarded as the beginning of the canal; since the course of the river being quite free on the right, the intervention of these islets and the dikes, of which we have already spoken, must obstruct the waters on the left, as far as to the place where there was formerly another waterfall called Presteskedet. It should seem, then, that one might provide sufficiently against the inconveniences of the floods by simply making the dikes or wears of a height equal to the depth of the water required for the navigation, thus letting them serve as a discharger, and a surface-sluice always open to the requisite level. But if, in addition to this, there were to be constructed, in the body of the wear which joins Melgon to the lower lip of the canal, some other dischargers and bottom-sluices, which should be made to play at proper seasons, the upper bed might be cleared of the various substances that must necessarily be collected there, in consequence of the retardation of the stream.

LXVII. The substances which are mixed with the water form, in length of time, the most serious obstructions in navigable canals. No precautions taken to prevent them can be deemed to be useless or superfluous. But in all particular cases a careful inspection of the spot is absolutely necessary: plans and descriptions, however accurate, will not suffice to give a stranger the necessary information for forming a correct judgment of what may be the issue of events. The great rapidity of the Gotha, the mountains between which it is enclosed, the reasons why the works of 1751 were ruined,—all announce that this river

must carry gravels, and other gross substances, in quantities sufficient to be transported and to extend through the whole length of the canal. Moreover, as the canal is to be excavated on the sides of the mountains in four different places, and for spaces of considerable length, the rains alone, independently of the common turbids of the river, will necessarily bring down other gross matters, in the same manner as the little torrents, and the rains, which descend from the neighbouring heights, carry sands and gravels into our canals of Milan, even beyond the spots to which those of the Tesino and the Adda are transported. From these conjectures, and from what has taken place in other instances, one may venture to prognosticate what may probably happen to this canal in the course of time.

LXVIII. In the first place, then, the turbids flowing through the opening and the first trunk of the canal into the little field (Plate II. 4), which, as far as I can conjecture from the plans, must be laid under water, will produce a repetition of the case mentioned in paragraph XVII. of the reservoir of Naurose and the Canal of Languedoc. In time, the substances there deposited will interrupt the navigation; and then it will become necessary to continue the canal in a straight line quite across the field. The same will happen to the lower field (Plate II. 11), which also must be laid under water, and where it is not intended to continue the canal. As its extent is very considerable, the accumulations will begin at the entrance, and it will be constantly necessary to have recourse to manual labour to keep the passage free and open. The canal will thus be gradually prolonged, and it will ultimately happen that there will

be but one single uniform channel from the entrance of the water as far as to the locks. This event will occur sooner or later in proportion to the size and the quantity of the substances deposited by the waters.

LXIX. This inconvenience, which probably has been already foreseen, in regard to laying these fields under water, may suggest a very good and certain mode of consolidating the whole of the morass (Plate II. 9, 9), which lies between the two fields in question, and through which the canal must run. When the upper trunk is entirely excavated, all that will be needed is, to introduce the turbid waters into the morass, and to direct them opportunely to those places where it is the deepest, and where the soil is the most loose: they will infallibly fill it up, and give it the proper consistence, and that the more speedily in proportion as the quantity of substances brought down by the stream shall be the greater. The Tuscans are complete masters of this mode of melioration, which is properly termed *filling up.* They have made great use of it, particularly in the Valdichiana. It is in this manner, that in the Polesines, in the Modenese, and in other parts of Italy, they have found the means of changing into rich lands marshes that lay waste and uncultivated. It would require some little time to complete the melioration of the morass of which we have been speaking; but they will be well repaid for the delay by the more certain and easy continúation of the whole canal.

LXX. It appears that, to render this undertaking more certainly successful, and more durable, it would be prudent to construct a third discharger immediately above the first sluice; and, further, that it would be requisite to be guided in the construction of this sluice

by the quality of the substances that might be brought down.—These are all the instructions which it is in my power to afford from a simple inspection of the surveys, and which I can venture to insert in this Essay. It is not merely as a man, as a citizen, and as a philosopher, that I feel interested in the success of so grand and so important a design. The honour conferred on me by my being elected a Member of the Royal Academy of Sweden,—the private friendship that unites me to several of the members of this illustrious body,—the esteem that I bear to so enlightened a nation, as polite as they are industrious,—all conspire to render me peculiarly solicitous that this work may be brought to a happy termination.

THE END.

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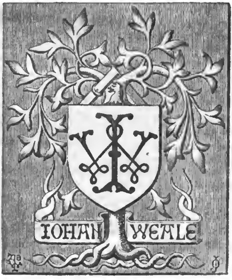

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